DIGITAL SIMULATION OF TRANSIENTS OF THE STEAM GENERATOR OF PRESSURIZED WATER NUCLEAR REACTOR

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NUCLEAR ENGINEERING TECHNOLOGY PROGRAMME

INDIAN INSTITUTE OF TECHNOLOGY, KANPUR

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DIGITAL SIMULATION OF TRANSIENTS OF THE STEAM GENERATOR OF PRESSURIZED WATER NUCLEAR REACTOR

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CERTIFICATE

This is to certify that this work on "Digital Simulation of Transients of the Steam Generator of Pressurized Water Nuclear Reactor" has been carried out under my supervision and it has not been submitted elsewhere for a degree.

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NOMENCLATURE

A - Cross sectional area for flow, ft^2

A_T - Heat transfer area, ft^2

C_P - Specific heat at constant pressure, Btu/lbm

D_e - Equivalent diameter, ft

$\bar{d}$ - Spacing of the tubes, inch.

d_e - External diameter of the tubes of primary circuit, inch.

d_i - Internal diameter of the tubes of primary circuit, inch.

e - Energy per unit mass, Btu/lbm

F_K - Frictional force, lbf

f - Friction coefficient

G - Mass flux, lbm/ft^2-hr

g - Acceleration due to gravity, ft/sec^2

g_c - Conversion ratio, $lbm-ft/lbf-sec^2$

H - Specific enthalpy, Btu/lbm

H_{fg} - Latent heat of vaporazition, Btu/lbm

H_{in} - Enthalpy at the inlet of the generator, Btu/lbm

h - Heat transfer coefficient, $Btu/hr-ft^2-^oF$

J - Mechanical equivalent of heat, $J = 778$ lbf-ft/Btu

k - Thermal Conductivity, $Btu/hr-ft-^oF$

L_{ev} - Length of the evaporator, ft

L_{PA} - Length of the preheater, ft

P_m - Wetted perimeter, ft

P - Pressure, Psi

ΔP - Pressure drop, Psi

Q - Rate of heat transfer, Btu/hr

$\ddot{q}$ - Heat flux, Btu/hr-ft^2

T - Temperature, ^oF

T_P - Temperature of the wall of the tube, ^oF

ΔT_{sat} - $T_P - T_{Sat}$, ^oF

u - Internal energy, Btu/lbm

U - Total internal energy, Btu/lbm

V - Velocity, ft/hr

v - Specific volume, ft^3/lbm

W - Mass flow rate, lbm/hr

x,X - Quality of vapour

X_{tt} - Lockhart and Martinelli's parameter

Z - Direction of flow

ΔZ - Height of each control volume, ft.

Greek Letters:

α - Void fraction.

μ - Viscosity, lbf/hr-ft

ρ - Density, lbm/ft^3

σ - Surface tension, lbf/ft

ϕ^2_{LO} - Multiplicator for calculating frictional pressure drop in two-phase flow.

γ - Empirical constant used in Thom's correlation for calculating the void-fraction.

Superscript:

$\bar{}$ - Refers to the value at the middle of a control volume.

Subscript:

e - Refers to the exit

ev - Evaporator

f - Saturated liquid condition

g - Saturated vapour condition

i - Inlet condition

iso - Refers to isothermal condition

j - Refers to junction

l - Saturated liquid.

P - Refers to primary circuit

PA - Refers to preheater

S - Refers to secondary circuit

Sat - Saturation condition

v - Saturated vapour condition

c.v. - Control volume

Dimensionless Groups:

Nu - Nusselt No. = $h.D_e/k$

Pr - Prandtl No. = $\mu.C_p/k$

Re - Reynolds No.= $G.D/\mu$.

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ABSTRACT

A digital computer code was developed to simulate the transient behaviour of a steam generator typically used in pressurized water reactor nuclear power plants.

The three fundamental equations of conservation of mass, energy and momentum were converted to a set of linear algebraic equations using finite difference method, from which an explicit numerical scheme was formulted.

On the primary side single phase flow and forced convection heat transfer were assumed and on the secondary side the possibility of the existence of different flow regimes was assumed and the heat transfer in these regimes was calculated using appropriate correlations.

CHAPTER 1

INTRODUCTION

1.1 Introduction:

With the present interest in the safety studies of nuclear reactor behaviour, it becomes important to study the behaviour of various reactor components. Steam generator forms an integral part of the nuclear power plants where heat is exchanged between the primary coolant, which flows through the core of the nuclear reactor, and the secondary fluid, which provides power for the turbine. The steam generator presents complexity in modeling because, even under normal conditions both subcooled and boiling heat transfer occur on the secondary side.

Modeling of a large system via state variable methods is quite difficult because of the fact that the overall system has to be broken down into separate models for each of the sub-systems and then these sub-sysbem models have to be coupled to construct the overall system model.

Dynamic modeling plays an important role particularly in nuclear power plants because of stringent safety requirements to ensure failsafe operation of the plant. Though a great deal of care is taken to ensure public safety in nuclear power plants there is always a finite probability that a system may fail and lead to an undesirable situation. Transient analysis allows us

to study the degree of danger one may encounter due to the failure of an equipment under a disturbed condition and it gives guidelines for proper instrumentation to prevent such accidents. In case of a steam generator a large number of possibilities which may perturb its steady operation can be enumerated. The steam generator has primary and secondary circuit. In the primary circuit there may be reduced flow rate of liquid due to loss of coolant accident (LOCA) wh ch generally occurs due to the rupture in the pipe, discharge from the high-pressure system to a low-pressure system. There may also be loss of flow accidents (LOFA) due to the improper opening of valves and pump failure. This disturbance in coolant flow in turn affects the pressure and the temperature of of the liquid in the primary heat transport system. Similarly the change in the feed water flow in the secondary circuit will alter the steam output and this may upset the operation of the turbines which will affect the power output of the whole power station. So transient analysis of the steam generator is essential to ensure that it can accommodate a certain amount of perturbation and does not fail to complicate the situation if there is an accident.

1.2 Review of Dynamic Models for Steam Generators:

In the literature there are no simplified models available for simulating the steam generators excepting the complicated

models of the reactor thermal hydraulic computer codes such as RELAP-4 [1] and FLASH [2] etc.

Recently a mathematical model was developed by Arwood and Kerlin [3] to simulate the U-tube steam generator. This paper uses linearized equations to predict the behaviour around a steady state operating point. The detailed heat transfer regimes are not considered explicitly.

Hoeld [4] developed a nonlinear transient model for the calculation of the dynamic behaviour of a vertical natural-circulation U-tube steam generator (UTSG). But modern nuclear power plants use IEUTSG which is an improved version of UTSG and has higher heat transfer effectiveness.

I.M.D. Silva [5] developed a model for simulating the transients of an IEUTSG. This model takes various flow regimes and different heat transfer regimes into account and follows an implicit numerical technique for calculating the dynamic behaviour of the steam generator.

1.3 Present Work:

The present work consists of developing a model to simulate the transient behaviour of an integral economizer U-tube steam generator (IEUTSG) utilized in a 600 MW_e PWR. To give an accurate representation of the steam generator, due considerations have been given to the aspects of two-phase flow and heat transfer.

As fundamental equations the well-known conservation equations for mass, energy and momentum have been chosen. Additional approximation equations for the thermo dynamic properties of water and steam, for a two-phase correlation, for one and two-phase friction coefficients and for the heat conduction coefficients have been established.

For steady state (starting) values the model and computer code developed by Armando Costa Pinto [6] has been used.

CHAPTER 2

THE STEAM GENERATOR

2.1 A brief description of the steam generator [7]:

A schematic of the steam generator is given in figure 2.1. Various components that constitute the steam generator are:

(a) Primary Side:

The hot primary fluid coming from the nuclear reactor enters the steam generator at the primary inlet plenum. The fluid then enters the upward portion (hot leg) of the U-tubes. The primary flow continues into the downward side (cold leg) and into the economizer section.

(b) Tube Metal Walls:

The tube metal walls separate the primary and the secondary fluids. Heat is transferred from the primary to the secondary fluid through the tube walls at a rate determined by the overall heat transfer coefficient and the temperature difference.

(c) Secondary Side:

In this side there is an economizer just above the bottom plenum. This economizer is nothing but a closed container which covers a portion of the cold legs and separates them from the rest of the secondary side. The

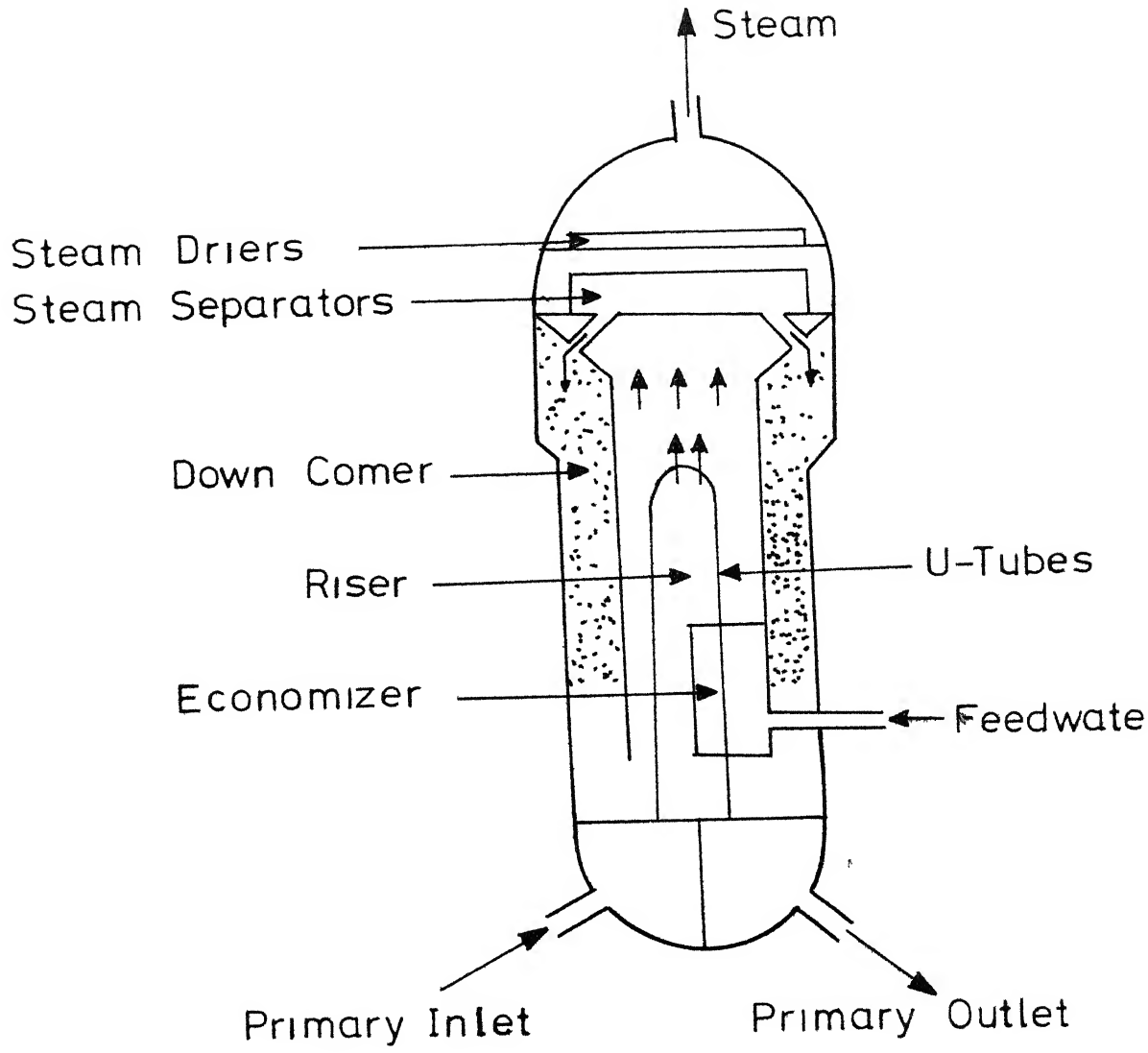


Fig. 2·1 A schematic of an Integral Economi
U-Tube Steam Generator (IEUTSG)

feedwater enters the evaporator through this economizer.

The IEUTSG design is a modification of the recirculation type U-tube steam generator (UTSG) used in many operating PWR's. The design change has been made to increase the heat transfer effectiveness of the system. The standard UTSG design is similar to that of the IEUTSG, but all of the feedwater is introduced into the downcomer and there is no economizer section. Because of the high recirculation ratio, the water entering the heated section from the downcomer is near the saturation temperature. As a result, there is a small temperature difference between the primary water of the cold legs and the secondary water in a UTSG. The purpose of the introduction of colder feedwater directly into this region in the IEUTSG design is to increase the temperature difference and increase the heat transfer from the primary water.

2.2 Model of the steam generator [6]:

The steam generator model used in the present study is shown in Fig. 2.2. The steam generator is represented in two sections, preheater (economizer) and an evaporator. In reality the steam generators of the PWR's have U-tube geometry, the present model simplifies it to parallel tube geometry but retains all the significant factors such as the total heat transfer area, total amount of heat transferred, preheater. Lack of detailed data about the internals of the steam generator, such

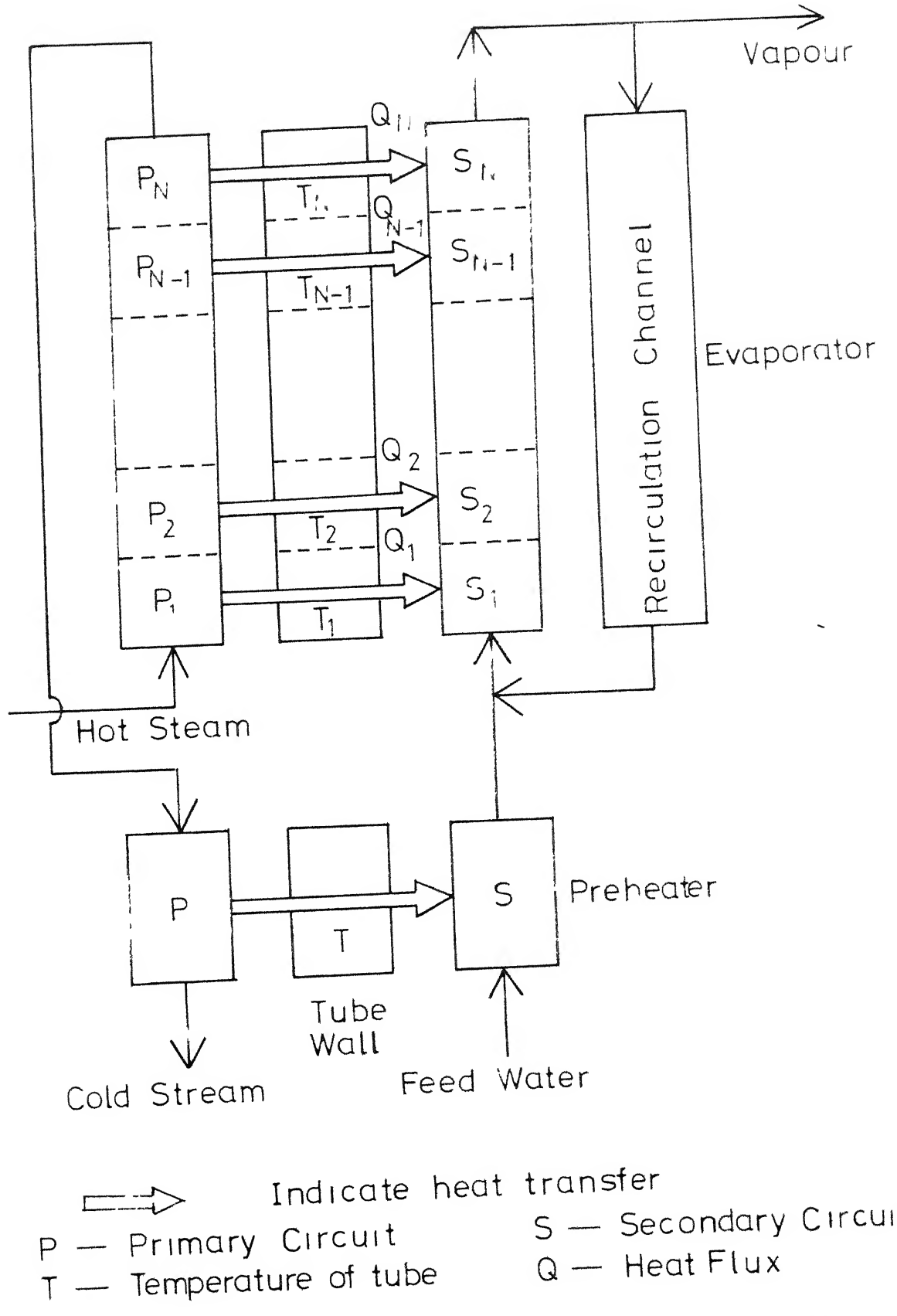


Fig. 2 2 Simulation model of Steam Generator

as the pressure drop due to baffles, quality of steam at the outlet of the generator before the steam oseparator etc. is circumvented by the pressure balance and heat balance equations as described in the later chapters.

As indicated in the figure the coolant from the reactor outlet enters the primary side of the generator as a hot stream in the evaporator section and leaves the generator from the preheater section as a cold stream to enter the reactor. The heat flow from the primary side is conducted through the tube walls of the steam generator and enters the secondary stream. The figure also indicates that the secondary stream leaves the evaporator section of the generator as vapor and part of the stream is recirculated. Some make up feedwater enters the preheater section and mixes with the secondary stream after the preheater.

CHAPTER 3

Analytical Model for Simulating the Steam Generator

3.1 Model for the steady state:

A simplified mathematical model and a computer code were developed by A.C. Pinto [7] for the steady state analysis of a steam generator utilized in a 600 MW_e pressurized water reactor nuclear power plants. This model takes different flow patterns and the corresponding heat transfer regimes into account. The details of this model can be found in reference 6. However, a brief description of this model is given in the following sections.

3.1.1 Fundamental equations of conservation:

In the steady state model [7] it is assumed that the flow is vertical. There is no transfer of work across each control volume indicated in Fig. 2.2. The area of flow cross section is assumed constant. Thus the three fundamental equations of mass, energy and momentum conservation become

Mass
$$A \frac{\partial \rho}{\partial t} = - \frac{\partial W}{\partial Z} \qquad (3.1)$$

where $W = \rho AV$.

Energy:
$$A \frac{\partial}{\partial t} (\rho_e) = \ddot{q} \frac{\partial A_T}{\partial Z} - \frac{\partial (We)}{\partial Z} - \frac{\partial}{\partial Z}(PAV) \qquad (3.2)$$

where $e = u + V^2/2 + gZ$ is the energy per unit mass of the fluid.

Momentum: $$A \cdot \frac{\partial(\rho V)}{\partial t} = - A\frac{\partial P}{\partial Z} - \frac{\partial F_K}{\partial Z} - A\rho g - \frac{\partial(WV)}{\partial Z} \qquad (3.3)$$

3.1.2 Equations of conservation at steady state:

At steady state the rate of change of any property with respect to time is zero. So the equations 3.1, 3.2 and 3.3 will become

$$W = \text{Constant} \qquad (3.4)$$

$$\ddot{q}\frac{dA_T}{dZ} - \frac{d(W_e)}{dZ} - \frac{d}{dZ}(PAV) = 0 \qquad (3.5)$$

$$- A\frac{dP}{dZ} - \frac{dF_K}{dZ} - \frac{d(WV)}{dZ} - A\rho g = 0 \qquad (3.6)$$

3.1.3 Equation of conservation of energy [7]:

Using the relations

$$e = u + \frac{V^2}{2} + gZ$$

$$H = u + \frac{P}{\rho}$$

$$W = \rho AV$$

$$G = W/A$$

$$v = 1/\rho$$

the equation 3.5 can be transformed to the following form (for details see appendix A):

$$\ddot{q} \frac{dA_T}{dZ} - W \frac{dH}{dZ} - WG^2 v \frac{dv}{dZ} - Wg = 0 \qquad (3.7)$$

Integrating this equation with respect to Z from junction n to n+1, the limits of control volume n, we get

$$H_{n+1} = H_n + \frac{\bar{Q}_n}{W} - \frac{G^2}{2 \cdot g_c \cdot J} (v_{n+1}^2 - v_n^2) - \frac{g}{g_c} \cdot \frac{1}{J} \cdot \Delta Z \qquad (3.8)$$

where $\bar{Q}_n = \int_{\text{Control volume n}} \ddot{q} \, dA_T = \ddot{q}_n \cdot A_T$ is the total amount of heat transfer in control volume n.

3.1.4 Equation of conservation of momentum [7]:

Let us integrate the equation 3.6 with respect to Z from the centre of control volume (n-1) to that of control volume n. The following two assumptions are made to simplify the integration.

(a) The frictional pressure in one half of any control volume is equal to one half of the frictional pressure of the whole control volume.

(b) The velocity of fluid at the outlet of control volume (n-1) is equal to the velocity of the fluid at the inlet of control volume n.

Utilizing these two assumptions and the relationship $G = W/A$, we get (for details see appendix B) the following equation.

$$\bar{P}_n = \bar{P}_{n-1} - \frac{1}{2 \cdot A} (\bar{F}_{K,n-1} + \bar{F}_{K,n}) - \frac{G}{144 \cdot g_c} (V_n - \bar{V}_{n-1})$$

$$- \frac{G}{144 \cdot g_c} (\bar{V}_n - V_n) - \frac{g}{144 \cdot g_c} \cdot \frac{\Delta Z}{v_n} \qquad (3.9)$$

The quantity without bar represents the value at the junction and the quantity with bar represents the average value in a control volume.

An examination of the terms of equation 3.9 will lead it to the following familiar form.

$$\bar{P}_n = \bar{P}_{n-1} - \frac{1}{2} [(\Delta P_{frictional})_{C.V.(n-1)} + (\Delta P_{frictional})_{C.V.(n)}]$$

$$- (\Delta P_{acceleration})_{C.V.(n-1)\ j.n} - (\Delta P_{acceleration})_{j.n\ C.V.(n)}$$

$$- (\Delta P_{elevation}) \qquad (3.10)$$

3.1.5 Flow patterns and heat transfer [6]:

The liquid in the primary heat transport system of the steam generator is always in the form of compressed liquid and hence the mode of heat transfer is pure convection. On the secondary side the liquid enters the generator as saturated

liquid. The secondary liquid will encounter bubbly flow and annular flow regimes and the heat transfer regimes will be pure convection, local boiling, nucleate boiling, forced convection and stable film boiling. The various flow regimes and the heat transfer modes and the correlations used in each mode are indicated in Table 3.1

3.2 Mathematical Model for Simulating the Transients

The model developed to simulate the transients of the steam generator has been described in details in the following sections.

3.2.1 Equations of conservation for analysing the transients:

The conservation equations are:

Mass: $$A \frac{\partial \rho}{\partial t} = - \frac{\partial W}{\partial Z} \qquad (3.11)$$

Energy: $$A \frac{\partial(\rho e)}{\partial t} = q \frac{\partial A_T}{\partial Z} - \frac{\partial (We)}{\partial Z} - \frac{\partial (PAV)}{\partial Z} \qquad (3.12)$$

Momentum: $$A \frac{\partial(\rho V)}{\partial t} = -A \frac{\partial P}{\partial Z} - \frac{\partial F_K}{\partial Z} - A\rho g - \frac{\partial (WV)}{\partial Z} \qquad (3.13)$$

where $e = u + V^2/2 + gZ$ is the energy per unit mass of the fluid. It can be assumed that the effect of g is negligibly small and hence the term gZ in the expression of e and $A\rho g$ of equation 3.13 can be neglected.

Mode	Flow Regime	Heat Transfer Regime	Heat Transfer Correlation
1	Single phase compressed liquid	Pure convection	Dittus Boelter equation [9]: $N_u = 0.023\ Re^{0.8}\ Pr^{0.4}$
2	Single phase compressed liqhid	Local boiling	Thom's correlation [9] $T_p - T_{Sat} = \frac{0.072\ (\ddot{q})^{1/2}}{Exp(P/1260)}$
3	Bubbly flow	Nucleate boiling	
4	Annular flow	Evaporation by forced convection	Chen's correlation [8]: $h = S(0.00122)A + F(0.023)Re_l^{0.8}\ Pr_l^{0.4}.\ \frac{k_l}{D_e}$ $A = \frac{k_l^{0.79}\ C_l^{0.45}\ \rho_l^{0.49}\ g_c^{0.25}\ \Delta T^{0.24}\ \Delta P^{0.75}}{\sigma^{0.5}\ \mu_l^{0.29}\ H_{fg}\ \rho_v^{0.20}}$ F and S are obtained using the polynomials given in chapter 5.
5	Annular flow	Stable film boiling	Polomik's correlation [9]: $\frac{h\ D_e}{k_{film}} = 0.0136\ (Re_{film}\ \frac{1-x}{x})^{0.853}\ \frac{\alpha}{1-\alpha}\ Pr_{film}$

Table 3.1

3.2.2 Equation of conservation of energy:

Using $e = u + V^2/2$ the equation 3.12 can be written as

$$A\frac{\partial(\rho u + \rho V^2/2)}{\partial t} = \ddot{q}\frac{\partial A_T}{\partial Z} - \frac{\partial(Wu + WV^2/2)}{\partial Z} - \frac{\partial}{\partial Z}(PAV)$$

which on simplification yields

$$A\frac{\partial(\rho u)}{\partial t} + A\rho V\frac{\partial V}{\partial t} + \frac{AV^2}{2}\frac{\partial \rho}{\partial t} = \ddot{q}\frac{\partial A_T}{\partial Z} - \frac{\partial(Wu)}{\partial Z} - WV\frac{\partial V}{\partial Z} - \frac{V^2}{2}\cdot\frac{\partial W}{\partial Z} - \frac{\partial}{\partial Z}(PAV)$$

Substituting in this equation the value of $A\frac{\partial \rho}{\partial t}$ we get on simplification

$$A\frac{\partial(\rho u)}{\partial t} = \ddot{q}\frac{\partial A_T}{\partial Z} - A\rho V\frac{\partial V}{\partial t} - \frac{\partial(Wu)}{\partial Z} - \frac{\partial(PAV)}{\partial Z} - WV\frac{\partial V}{\partial Z} \quad (3.12a)$$

From equation 3.13 we get

$$A\rho\frac{\partial V}{\partial t} + AV\frac{\partial \rho}{\partial t} = -A\frac{\partial P}{\partial Z} - W\frac{\partial V}{\partial Z} - V\frac{\partial W}{\partial Z} - \frac{\partial F_K}{\partial Z}$$

Multiplying both sides by V and substituting the value of $A\frac{\partial \rho}{\partial t}$ into this equation we get on simplification

$$A\rho V\frac{\partial V}{\partial t} = -AV\frac{\partial P}{\partial Z} - WV\frac{\partial V}{\partial Z} - V\frac{\partial F_K}{\partial Z} \quad (3.13a)$$

Substituting the value at $A\rho V\frac{\partial V}{\partial t}$ in the equation 3.12a it can be simplified to the following form.

$$A\frac{\partial(\rho u)}{\partial t} = \ddot{q}\frac{\partial A_T}{\partial Z} - \frac{\partial(Wu)}{\partial Z} - PA\frac{\partial V}{\partial Z} + V\frac{\partial F_K}{\partial Z} \qquad (3.12b)$$

3.2.3 System of equations:

We now have the following system of equations to be used to simulate the transients.

$$A\frac{\partial(\rho V)}{\partial t} = -A\frac{\partial P}{\partial Z} - \frac{\partial(WV)}{\partial Z} - \frac{\partial F_K}{\partial Z} \qquad (3.14)$$

$$A\frac{\partial(\rho u)}{\partial t} = \ddot{q}\frac{\partial A_T}{\partial Z} - \frac{\partial(Wu)}{\partial Z} - PA\frac{\partial V}{\partial Z} + V\frac{\partial F_K}{\partial Z} \qquad (3.15)$$

$$A\frac{\partial \rho}{\partial t} = -\frac{\partial W}{\partial Z} \qquad (3.16)$$

Integration of these equations with respect to Z over a control volume i bounded by junction i and i+1 will lead to the following forms.

(a) The equation of momentum conservation gives:

$$\frac{\partial}{\partial t}\int_i^{i+1} A\rho V\,dz = -\int_i^{i+1}\frac{\partial(WV)}{\partial Z}\,dz - \int_i^{i+1}\frac{\partial F_K}{\partial Z}\,dz - A\int_i^{i+1}\frac{\partial P}{\partial Z}\,dZ$$

Let us define $\overline{W}_i = \dfrac{\int_i^{i+1} A\rho\, V\, dz}{\int_i^{i+1} dZ}$

With this definition we get

$$\Delta Z \frac{d\bar{W}_i}{dt} = -A(P_{i+1} - P_i) - [WV|_{i+1} - WV|_i] - \bar{F}_{Ki}$$

But $W = \rho AV$, i.e., $WV = W^2/\rho A$ and

$$\bar{F}_{Ki} = \bar{f}_i \frac{W_i^2}{2\,AD_e\,\rho_i} \Delta Z$$

So the momentum equation takes the form:

$$\bar{W}_i = \frac{A}{\Delta Z}(P_i - P_{i+1}) + \frac{1}{A \cdot \Delta Z}\left(\frac{W_i^2}{\rho_i} - \frac{W_{i+1}^2}{\rho_{i+1}}\right) - \bar{f}_i \frac{W_i^2}{2AD_e\,\rho_i}$$

(3.17)

(b) The equation of energy conservation will give:

$$\frac{\partial}{\partial t}\int_i^{i+1} A\rho u\, dZ = \int_i^{i+1} \ddot{q}\frac{\partial A_T}{\partial Z}\, dZ - \int_i^{i+1} \frac{\partial(wu)}{\partial Z}\, dZ - \int_i^{i+1} PA\frac{\partial V}{\partial Z}\, dZ + \int_i^{i+1} V\frac{\partial F_K}{\partial Z}\, dZ$$

We now define

$$\bar{U}_i = \int_i^{i+1} A\,\rho u\, dZ$$

$$\bar{Q}_i = \int_i^{i+1} \ddot{q}\frac{\partial A_T}{\partial Z}\, dZ$$

$$\int_{i}^{i+1} PA \frac{\partial V}{\partial Z} \, dZ \quad \bar{P}_i \, A \, (V_{i+1} - V_i) = P_i \left(\frac{W_{i+1}}{\rho_{i+1}} - \frac{W_i}{\rho_i} \right)$$

and

$$\int_{i}^{i+1} V \frac{\partial F_K}{\partial Z} \, dZ = \bar{V}_i \, \bar{F}_{K,i} = \bar{f}_i \, \frac{\partial \bar{W}_i^3}{2A^2 D_e \bar{\rho}_i^2} \cdot \Delta Z$$

With these simplifying assumptions we get

$$\dot{\bar{U}} = \bar{Q}_i + W_i u_i - W_{i+1} u_{i+1} - {}_i \left(\frac{W_{i+1}}{\rho_{i+1}} - \frac{W_i}{\rho_i} \right)$$

$$+ \bar{f}_i \, \frac{\bar{W}_i^3}{2A^2 D_e \rho_i^2} \cdot \Delta Z \qquad (3.18)$$

(c) The equation of mass conservation gives:

$$\frac{\partial}{\partial t} \int_{i}^{i+1} A\rho \, dz = - \int_{i}^{i+1} \frac{\partial W}{\partial Z} \, dz$$

Let us define

$$\bar{\rho}_i = \frac{\int_{i}^{i+1} A\rho \, dz}{\int_{i}^{i+1} A \, dz}$$

With this definition we get

$$\dot{\bar{\rho}}_i = \frac{1}{A \cdot \Delta Z} \, (W_i - W_{i+1}) \qquad (3.19)$$

Equations 3.17, 3.18 and 3.19 have to be modified to incorporate the two-phase multiplier r and make the units consistent. To make the units consistent we have to multiply appropriate term by any one of the following three factors.

$$C_1 = g_c \times 3600^2 \ \frac{sec^2}{Hr^2} \times 144 \ \frac{in^2}{ft^2} = 0.600444 \times 10^{11}$$

$$C_2 = 144 \ \frac{in^2}{ft^2} \times 0.001285 \ \frac{Btu}{lbf\text{-}ft} = 0.18504$$

$$C_3 = \frac{1}{g_c} \times \frac{Hr^2}{3600^2 \ Sec^2} \times 0.001285 \ \frac{Btu}{lbf\text{-}ft} = 0.308172 \times 10^{-11}$$

Now we have

$$\dot{\bar{\rho}}_i = \frac{1}{A \cdot \Delta Z} (W_i - W_{i+1}) \qquad (3.20)$$

$$\dot{\bar{U}}_i = \bar{Q}_i + W_i u_i - W_{i+1} u_{i+1} - \bar{I}_i C_2 \left(\frac{W_{i+1}}{\rho_{i+1}} - \frac{W_i}{\rho_i}\right) + C_3 \frac{\bar{f}_i \bar{W}_i^3 \Delta Z}{2A^2 D_e \bar{\rho}_i^2} \qquad (3.21)$$

$$\dot{\bar{W}}_i = \frac{C_1 A}{\Delta Z} (P_i - P_{i+1}) - \frac{\bar{f}_i \bar{W}_i^2}{2A D_e \bar{\rho}_i} + \frac{1}{A \cdot \Delta Z} \left(r_i \frac{W_i^2}{\rho_i} - r_{i+1} \frac{W_{i+1}^2}{\rho_{i+1}}\right) \qquad (3.22)$$

Now we will proceed to express the junction variables in terms of control volume variables.

It is assumed that

$$\bar{W}_i = \tfrac{1}{2}(W_i + W_{i+1}), \text{ i.e., } W_{i+1} = 2\bar{W}_i - W_i$$

$$\bar{u}_i = \tfrac{1}{2}(i_i + u_{i+1}), \text{ i.e., } u_{i+1} = 2\bar{u}_i - u_i$$

$$\bar{\rho}_i = \tfrac{1}{2}(\rho_i + \rho_{i+1}), \text{ i.e., } \rho_{i+1} = 2\bar{\rho}_i - \dot{\rho}_i$$

Let us define specific internal energy

$$\bar{u}_i = \frac{\int_i^{i+1} A\rho u \, dz}{\int_i^{i+1} A\rho \, dz} = \frac{\bar{U}_i}{A \Delta Z \bar{\rho}_i}.$$

Pressure P_i can be expressed as a function of u_i and $_i$, i.e.,

$$P_i = P_i(u_i, \rho_i)$$

These variables will take the following form at junction 2:

$$W_2 = 2\bar{W}_1 - W_1$$

$$u_2 = 2\bar{u}_1 - u_1$$

$$\rho_2 = 2\bar{\rho}_1 - \rho_1$$

$$P_2 = P_2(u_2, \rho_2) = P_2(2\bar{u}_1 - u_1, \; 2\bar{\rho}_1 - \rho_1)$$

$$= P_2(\bar{u}_1, \bar{\rho}_2, u_1, \rho_1).$$

At junction 3:

$$W_3 = 2\,\bar{W}_2 - W_2 = 2\,\bar{W}_2 - (2\,\bar{W}_1 - W_1)$$

$$= 2\,\bar{W}_2 - 2\,\bar{W}_1 + W_1$$

Similarly,

$$u_3 = 2\,\bar{u}_2 - 2\,\bar{u}_1 + u_1$$

$$\rho_3 = 2\,\bar{\rho}_2 - 2\,\bar{\rho}_1 + \rho_1$$

$$P_3 = P_3\,(\bar{u}_2,\ \bar{u}_1,\ \bar{\rho}_2,\ \bar{\rho}_1,\ u_1,\ \rho_1)$$

At junction 4 :

$$W_4 = 2\,\bar{W}_3 - 2\,\bar{W}_2 + 2\,\bar{W}_1 - W_1$$

$$u_4 = 2\,\bar{u}_3 - 2\,\bar{u}_2 + 2\,\bar{u}_1 - u_1$$

$$\rho_4 = 2\,\bar{\rho}_3 - 2\,\bar{\rho}_2 + 2\,\bar{\rho}_1 - \rho_1$$

$$P_4 = P_4(\bar{u}_2,\ \bar{u}_1,\ u_1,\ \bar{\rho}_3,\ \bar{\rho}_2,\ \bar{\rho}_1,\ u_1,\ \rho_1)$$

At junction n:

$$W_n = 2\,\bar{W}_{n-1} - 2\,\bar{W}_{n-2} + 2\,\bar{W}_{n-3} - \cdots\cdots + (-1)^{n-1}\,W_1$$

for n = 2, 3, 4, ..., N.

i.e.,

$$W_n = (-1)^{n-1} W_1 + 2 \sum_{K=1}^{n-1} (-1)^{n+k-1} \bar{W}_K$$

for n = 2, 3, 4, ..., N.

Similarly for n = 2, 3, 4,...., N.

$$u_n = (-1)^{n-1} u_1 + 2 \sum_{K=1}^{n-1} (-1)^{n+K-1} \bar{u}_K$$

$$\rho_n = (-1)^{n-1} \rho_1 + 2 \sum_{K=1}^{n-1} (-1)^{n-K-1} \bar{\rho}_K$$

and $P_n = P_n(\bar{u}_{n-1}, \bar{u}_{n-2}, ..., \bar{u}_1, \bar{\rho}_{n-1}, ..., \bar{\rho}_1, u_1, \rho_1)$

Using these expressions the equations 3.20, 3.21 and 3.22 can be written as

$$\dot{\bar{\rho}}_n = \frac{1}{A\Delta Z} \left[\{(-1)^{n-1} W_1 + \sum_{K=1}^{n-1} (-1)^{n+K-1} 2 \bar{W}_K \} \right.$$

$$\left. - \{(-1)^n W_1 + \sum_{k=1}^{n} (-1)^{n+K} 2 \bar{W}_K \} \right] \qquad (3.23)$$

$$\dot{\bar{U}}_n = \bar{Q}_n + \left[(-1)^{n-1} W_1 + \sum_{K=1}^{n-1} (-1)^{n+K} 2 \bar{W}_K \right] \times \left[(-1)^{n-1} u_1 \right.$$

$$\left. + \sum_{K=1}^{n-1} (-1)^{n+K-1} 2 \bar{u}_K \right] - \left[(-1)^n W_1 + \sum_{K=1}^{n} (-1)^{n+K} 2 \bar{W}_K \right]$$

$$\times \left[(-1)^n u_1 + \sum_{K=1}^{n} (-1)^{n+K} 2 \bar{u}_K \right]$$

$$- \bar{P}_n \, C_2 \left[\frac{(-1)^n \, W_1 + \sum_{K=1}^{n} (-1)^{n+K} \, 2 \, \bar{W}_K}{(-1)^n \, \rho_1 + \sum_{K=1}^{n} (-1)^{n+K} \, 2 \, \bar{\rho}_K} - \frac{(-1)^{n-1} \, W_1 \sum_{K=1}^{n} (-1)^{n+K-1} \, 2 \bar{W}_K}{(-1)^{n-1} \, \rho_1 \sum_{K=1}^{n-1} (-1)^{n+K-1} \, 2 \bar{\rho}_K} \right]$$

$$+ C_3 \cdot \bar{f}_n \frac{\bar{W}_n^{\,3}}{2A^2 \, D_e \, \bar{\rho}_i^{\,2}} \cdot \Delta Z \qquad (3.24)$$

$$\dot{\bar{W}}_n = \frac{C_1 A}{\Delta Z} \, P_n(\bar{u}_{n-1}, \bar{u}_{n-2}, \ldots, \bar{u}_1, \bar{\rho}_{n-1}, \bar{\rho}_{n-2}, \ldots, \bar{\rho}_1, u_1 \, \rho_1)$$

$$- \frac{C_1 A}{\Delta Z} \, P_{n+1}(u_n, u_{n-1}, u_{n-2}, \ldots, u_1, \bar{\rho}_n, \bar{\rho}_{n-1}, \ldots, \bar{\rho}_1, u_1, \rho_1)$$

$$+ \frac{r_n}{A \cdot \Delta Z} \times \frac{\left[(-1)^{n-1} \, W_1 + \sum_{K=1}^{n-1} (-1)^{n+K-1} \, 2 \, \bar{W}_K\right]^2}{\left[(-1)^{n-1} \, \rho_1 + \sum_{K=1}^{n-1} (-1)^{n+K-1} \, 2 \, \bar{\rho}_K\right]}$$

$$- \frac{r_n}{A \cdot \Delta Z} \times \frac{\left[(-1)^n \, W_1 + \sum_{K=1}^{n} (-1)^{n+K} \, 2 \, W_K\right]^2}{\left[(-1)^n \, \rho_1 + \sum_{K=1}^{n} (-1)^{n+K} \, 2 \, \bar{\rho}_K\right]}$$

$$- \bar{f}_n \frac{\bar{W}_n^{\,2}}{2A \, D_e \, \bar{\rho}_n} \qquad (3.25)$$

3.2.4 Solution of the system of equations:

Each control volume is represented by the equations 3.23, 3.24 and 3.25. So for each control volume there will be 3 equations with 3 unknowns. Porsching [10] had pointed out that for any thermal-hydraulic network involving the three basic

conservation equations, an explicit numerical scheme can be formulated which is consistent and stable for some appropriate time-step.

(a) Derivation of the numerical scheme:

Equations 4.13, 4.14 and 4.15 can be written as

$$\dot{\bar{\rho}}_i = F_j \ , \quad i = 1, 2, \ldots, N \text{ and } j = 1, 2, \ldots, N$$

$$\dot{\bar{U}}_i = F_j \ , \quad i = 1, 2, \ldots, N \text{ and } j = N+1, N+2, \ldots, 2N$$

$$\dot{\bar{W}}_i = F_j \ , \quad i = 1, 2, \ldots, N \text{ and } j = 2N+1, 2N+2, \ldots, 3N$$

Let us define

$$\underline{y} = \text{Vector } [\bar{\rho}_1, \bar{\rho}_2, \ldots, \bar{\rho}_N, \bar{U}_1, \bar{U}_2, \ldots, \bar{U}_N, \bar{W}_1, \bar{W}_2, \ldots, \bar{W}_N]$$

and

$$\underline{F}(t,y) = \text{Vector } [F_1, F_2, \ldots, F_N, F_{N+1}, F_{N+2}, \ldots, F_{2N}, F_{2N+1}, F_{2N+2}, \ldots, F_{3N}]$$

It can be written using these two definitions

$$\dot{\underline{y}} = \underline{F}(t, y)$$

So the equation to be solved is

$$\dot{\underline{y}} = \underline{F}(t,y) \quad \text{with the initial condition } \underline{y}(o) = \underline{y}_o.$$

The given differential equation can be written as

$$\frac{d\underline{y}}{dt} = \underline{F}(t, y)$$

i.e., $$\Delta \underline{y}^{n+1} = \underline{F}^{n+1} \Delta t$$

$$= \{ \underline{F}^{n} + \underline{F}^{n+1} - \underline{F}^{n} \} \Delta t$$

$$= \{ \underline{F}^{n} + \Delta \underline{F}^{n+1} \} \Delta t$$

If we approximate

$$\frac{dF}{dt}\Big|_{n} = \frac{\Delta F^{n+1}}{\Delta y^{n+1}}$$

then $$\Delta F^{n+1} = \frac{dF}{dt}\Big|_{n} \times \Delta y^{n+1}$$

So we now have

$$\Delta \underline{y}^{n+1} = [\underline{F}^{n} + \frac{dF}{dy}\Big|_{n} \Delta \underline{y}^{n+1}] \Delta t$$

i.e., $$[I - \frac{dF}{dy}\Big|_{n} \Delta t] \Delta \underline{y}^{n+1} = \underline{F}^{n} \Delta t$$

The matrix representation of this equation will be

$$\begin{bmatrix} 1-\Delta t \frac{\partial \dot{\bar{\rho}}_i}{\partial \bar{\rho}_i} & -\Delta t \frac{\partial \dot{\bar{\rho}}_i}{\partial \bar{U}_i} & -\Delta t \frac{\partial \dot{\bar{\rho}}_i}{\partial \bar{W}_i} \\ -\Delta t \frac{\partial \dot{\bar{U}}_i}{\partial \bar{\rho}_i} & 1-\Delta t \frac{\partial \dot{\bar{U}}_i}{\partial \bar{U}_i} & -\Delta t \frac{\partial \dot{\bar{U}}_i}{\partial \bar{W}_i} \\ -\Delta t \frac{\partial \dot{\bar{W}}_i}{\partial \bar{\rho}_i} & -\Delta t \frac{\partial \dot{\bar{W}}_i}{\partial \bar{U}_i} & 1-\Delta t \frac{\partial \dot{\bar{W}}_i}{\partial \bar{W}_i} \end{bmatrix} \begin{bmatrix} \Delta \bar{\rho}_i \\ \Delta \bar{U}_i \\ \Delta \bar{W}_i \end{bmatrix} = \begin{bmatrix} \dot{\bar{\rho}}_i \\ \dot{\bar{U}}_i \\ \dot{\bar{W}}_i \end{bmatrix} \Delta t$$

Before evaluating these derivatives let us first establish a few identities which will be used for the evaluation of the derivatives. It has been shown that

$$\rho_n = (-1)^{n-1} \rho_1 + 2 \sum_{K=1}^{n-1} (-1)^{n+K-1} \bar{\rho}_K$$

So $$\frac{\partial \rho_n}{\partial \bar{\rho}_j} = (-1)^{n+j-1} \cdot 2$$

and $$\frac{\partial \rho_{n+1}}{\partial \bar{\rho}_j} = (-1)^{n+j} \cdot 2$$

Similarly,

$$\frac{\partial u_n}{\partial \bar{u}_j} = (-1)^{n+j-1} \cdot 2$$

and

$$\frac{\partial u_{n+1}}{\partial \bar{u}_j} = (-1)^{n+j} \cdot 2$$

Also

$$\bar{u}_j = \frac{\bar{U}_j}{A\,\bar{\rho}_j\,\Delta Z}$$

i.e.,

$$\frac{\partial \bar{u}_j}{\partial \bar{U}_j} = \frac{1}{A\,\bar{\rho}_j\,\Delta Z}$$

Using these identities and taking the derivatives of equations 3.23, 3.24 and 3.25 with respect to $\bar{\rho}_i$, $\bar{U}_i$ and $\bar{W}_i$ for n = i and utilizing the following three notations.

$$W_m = (-1)^{m-1} W_1 + 2 \sum_{K=1}^{m-1} (-1)^{m+K-1} \bar{W}_K$$

$$u_m = (-1)^{m-1} u_1 + 2 \sum_{K=1}^{m-1} (-1)^{m+K-1} \bar{u}_K$$

$$\rho_m = (-1)^{m-1} \rho_1 + 2 \sum_{K=1}^{m-1} (-1)^{m+K-1} \bar{\rho}_K$$

We get

$$\frac{\partial \dot{\bar{\rho}}_i}{\partial \bar{\rho}_i} = 0$$

$$\frac{\partial \dot{\bar{\rho}}_i}{\partial \bar{U}_i} = 0$$

$$\frac{\partial \dot{\bar{\rho}}_i}{\partial \bar{W}_i} = -\frac{2}{A \cdot \Delta Z}$$

$$\frac{\partial \dot{\bar{U}}_i}{\partial \bar{\rho}_i} = -C_2 \left(\frac{\partial \bar{P}_i}{\partial \bar{\rho}_i}\right)\left(\frac{W_{i+1}}{\rho_{i+1}} - \frac{W_i}{\rho_i}\right) + C_2 \cdot \bar{P}_i \cdot 2 \cdot \frac{W_{i+1}}{\rho_{i+1}} - \bar{f}_i \cdot C_3 \frac{\bar{W}_i^3 \cdot \Delta Z}{A^2 \cdot D_e \cdot \bar{\rho}_i^2}$$

$$\frac{\partial \dot{\bar{U}}_i}{\partial \bar{U}_i} = -\frac{2W_{i+1}}{A \cdot \Delta Z \cdot \bar{\rho}_i} - C_2 \left(\frac{\partial \bar{P}}{\partial \bar{u}}\right)_i \left(\frac{W_{i+1}}{\rho_{i+1}} - \frac{W_i}{\rho_i}\right)$$

$$\frac{\partial \dot{\bar{U}}_i}{\partial \bar{W}_i} = -2u_{i+1} - C_2 \frac{2\bar{P}_i}{\rho_{i+1}} + \frac{3}{2} \cdot C_3 \frac{\bar{f}_i \bar{W}_i^2 \Delta Z}{A^2 \cdot D_e \cdot \bar{\rho}_i^2}$$

$$\frac{\partial \dot{\bar{W}}_i}{\partial \bar{\rho}_i} = -C_1 \frac{A}{\Delta Z} 2\left(\frac{\partial P}{\partial \rho}\right)_{i+1} + \frac{r_{i+1}}{A \cdot \Delta Z} \cdot \frac{W_{i+1}^2}{\rho_{i+1}} + \bar{f}_i \frac{\bar{W}_i^2}{2A D_e \bar{\rho}_i^2}$$

$$\frac{\partial \dot{\bar{W}}_i}{\partial \bar{U}_i} = -C_1 \frac{2}{\Delta Z^2 \bar{\rho}_i} \left(\frac{\partial P}{\partial u}\right)_{i+1}$$

$$\frac{\partial \dot{\bar{W}}_i}{\partial \bar{W}_i} = -\frac{\bar{f}_i \bar{W}_i}{A \cdot D_e \cdot \bar{\rho}_i} - \frac{4 \cdot 4_{i+1} W_{i+1}}{\bar{A} \cdot \Delta Z \cdot \rho_{i+1}}$$

Using these values in the above 3x3 matrix the values of $\Delta\bar{\rho}_i$, $\Delta\bar{U}_i$ and $\Delta\bar{W}_i$ can be calculated for each control volume and knowing these values ρ_i^{n+1}, $\bar{U}_i^{n+1}$ and $\bar{W}_i^{n+1}$ can be determined by using

$$\bar{\rho}_i^{n+1} = \bar{\rho}_i^{n} + \Delta\bar{\rho}_i$$

$$\bar{U}_i^{n+1} = \bar{U}_i^{n} + \Delta \bar{U}_i$$

$$\bar{W}_i^{n+1} = \bar{W}_i^{n} + \Delta \bar{W}_i$$

Once $\bar{\rho}_i^{n+1}$, $\bar{U}_i^{n+1}$ and $\bar{W}_i^{n+1}$ are known, other parameters can be easily determined.

CHAPTER 4

DESCRIPTION OF THE COMPUTER CODE

4.1 Input Variables:

The input to the computer code is fairly simple. Some of the data can be directly taken from the steam table. But other data have to be generated by polynomial regression using the data of compressed liquid (water).

The required input data cards are listed below. The units of each parameter and their input format are also included.

Card No.	Variable	Value	Format
1-118	AGUAS (I,1)	Saturation pressure in psi	F 10.4
	AGUAS (I,2)	Saturation temperature in ^{o}F	F 10.4
	AGUAS (I,3)	Sp. Vol. of liquid in ft^3/lbm.	F 10.4
	AGUAS (I,4)	Sp. Vol. of vapour in ft^3/lbm.	F 10.4
	AGUAS (I,5)	Sp. enthalpy of liquid in Btu/lbm	F 10.4
	AGUAS (I,6)	Sp. enthalpy of varpour in Btu/lbm	F 10.4

The cards are in decreasing order of saturation pressure.

119-126	((AGUAC (I,J), J = 1, 12), I = 1, 4)	

Format is 6E12.6 for each card and there will be 6 values on each card.

J = 12 different values of temperature

I = 1 Temperature

I = 2 Constant part

I = 3 Coefficient of P

I = 4 Coefficient of P^2

127	FREGB	Limits of quality regions	6F 10.4

6 values

128-166	COEFB(I,J)	Interpolated values	5E 15.6

((COEFB(I,J), J = 1, 15), I = 1, 13)

5 values on each card.

I=13 Quality for the curve

J=1,15 Indicates the pressure set to be used.

I=1-6 A for each set

I=7-12 B for each set

(COEFB(13,K), K=1,15) Quality of each of the 15 curves of Baroczy plot.

167-168	GAMAT	Gamma factor	7F 10.4

((GAMAT(I,J), J=1,7), I=1,2)

J=1 Indicates pressure

J=2 Indicates gama factor

Card No.	Variable	Value	Format
169	GNOME	Name of the programme	20A
170	NVC	No. of control volume	I3
	NMCL	Maximum No. of iterations	I3
	IESCR	Output option	I1
		= 0, Print final value	
		= 1, Print all iterations	
		= 2, Print all details	
	PRECQ	Precision required	F10.3
	GRAV	Acceleration due to gravity	F10.3
171	NTP	No.of U-tubes in primary	I7
	MALHA	Type of pitch	I1
		= 1, Square pitch	
		= 2, Triangular pitch	
	ATTC	Total heat transfer area (ft^2)	F10.2
	DEX	External diameter (inches)	F10.2
	DIN	Internal diameter(inches)	F10.2
	PASSO	Spacing between tubes (inches)	F10.2
	COEFF	Form factor	F10.2
172	PPJ(1)	Inlet steam pressure (Psi)	F10.2
	TPJ(1)	Inlet steam temperature (^oF)	F10.2

Card No.	Variable	Value	Format
	HPJ (1)	Inlet steam enthalpy (Btu/lbm)	F10.2
	PSP	Estimated primary pressure (Psi)	F10.2
	WP	Inlet flow rate in primary (lbm/hr)	E12.6
173	PEAA	Pressure of feed water (Psi)	F10.2
	TEAA	Temperature of feed water (^{o}F)	F10.2
	HEAA	Enthalpy of feed water (Btu/lbm)	F10.2
	PSS	Exit pressure (Psi)	F10.2
	XExit	Quality at exit	F10.2
	WS	Flow rate of feed water (lbm/hr)	E12.6
174	QTOT	Total heat transfer rate (Btu/hr)	E12.6
175	OP	Calculation option = 1, calculate only the steady state values ≠ 1, calculate both steady state values and transients.	I1
176-183	UFVAC(I,J)	Polynomials expressing internal energy (u) as a function of sp.vol.(v)	5X, F7.1, 5X, 3E16.5

((UFVAC(I,J), J=1,4), I=1,8)

4 values on each card.

Card No.	Variable	Value	Format
	I = 8	different values at pressure	
	J = 1	Pressure	
	J = 2	Constant part	
	J = 3	Coefficient of v	
	J = 4	Coefficient of v^2	
	The cards are in increasing order of the pressure. These are for compressed water.		
184-191	VFUAC(I,J)	Polynomials expressing sp.vol.(v) as a function of internal energy (u)	5X, F7.1, 5X, 3E16.5
	((VFUAC(I,J), J=1,4),I=1,8)		
	4 values on each card.		
	I = 8	different pressure values	
	J = 1	Pressure	
	J = 2	Constant part	
	J = 3	Coefficient of u	
	J = 4	Coefficient of u^2	
	The cards are in increasing order of the pressure. These are for compressed water.		
192	Time (Sec)	Duration over which the transient has to be calculated.	No format is needed
	NIT	No. of intervals	No format is needed

Card No.	Variable	Value	Format
193-207	VFPH (I,J)	Polynomials expressing sp.vol. (v) as a function of pressure (P) at constant enthalpy(h)	3X, F6.1, 3E19.7
	((VFPH (I,J), J=1,4), I=1,15)		
	4 values on each card.		
	I = 15	different enthalpy values.	
	J = 1	Enthalpy	
	J = 2	Constant part	
	J = 3	Coefficient of P	
	J = 4	Coefficient of P^2	
	The cards are in increasing order of the enthalpy.	These are for compressed water.	
208	VEPPJ (2)	Sp.Vol. of compressed water at the inlet condition of the pre-heater of primary circuit.	No format is needed
209	VESPJ (1)	Sp. volume of water at the inlet condition of the preheater of secondary circuit.	No format is needed

4.2 Steady state calculation:

For calculating the steady state values, i.e., the starting values for transient calculation the computer code and the model developed by A.C. Pinto [7] are used.

4.2.1 Flow-chart :

The procedure involved in the above computer code is given in the form of a flow-chart in figure 4.1. The function of various subroutines will be discussed in the next section.

4.2.2 Subroutines [7]:

(a) CPAGC - It calculates specific heat C_p of compressed water at constant pressure as a function of temperature(^oF) at various pressure range. The unit of specific heat is Btu/lb-^oF.

(i) $C_p = 0.14931.10^{-5}\ T^2 - 0.45187.10^{-3}\ T + 1.0241$ for $P \leq 1500$ Psi.

(ii) 1500 Psi $< P \leq$ 2500 Psi

$C_p = 0.90724.10^{-6}\ T^2 - 0.23174.10^{-3}\ T + 1.0049, \quad T \leq 300^oF$

$C_p = 0.38132.10^{-7}\ T^3 - 0.453.10^{-4}\ T^2 - 0.18281.10^{-1}\ T - 1.4375$ for $T > 300^oF$.

(iii) 2500 Psi $< P \leq$ 3500 Psi

$C_p = 0.90941.10^{-6}\ T^2 - 0.24668x10^{-3}\ T + 1.0028$ for $T \leq 300^oF$

$C_p = 0.47072.10^{-6}\ T^2 - 0.31944.10^{-2}\ T + 1.5651$

for $300\ ^oF < T \leq 620\ ^oF$

$C_p = 0.22404.10^{-6}\ T^3 - 0.10377.10^{-3}\ T^2 - 0.13194\ T + 69.772$

for $T > 620\ ^oF$.

(b) CPAGS - It calculates specific heat C_p of saturated water as a function of temperature T.

$C_p = 0.10313.10^{-5}\ T^2 - 0.25129.10^{-3}\ T + 1.0125$ for $T \leq 410^{\circ}F$

$C_p = 0.13446.10^{-4}\ T^2 - 0.11339.10^{-1}\ T + 3.4878$

for $410 < T \leq 630\ ^{\circ}F$

$C_p = 0.21005\ T - 11.543, \quad 630 < T \leq 660\ ^{\circ}F$

$C_p = 0.58005\ T - 35.97, \quad 660 < T \leq 680\ ^{\circ}F$

$C_p = 0.20068\ T - 132.97, \quad T > 680\ ^{\circ}F$

(c) CTAGC - It calculates the conductivity (k) of compressed water in Btu/hr-ft-$^{\circ}$F as a function of pressure (psi) and temperature ($^{\circ}$F).

(i) $P \leq 1500$ Psi

$k = 0.1131.10^{-5}\ T^2 + 0.64326.10^{-3}\ T + 0.30963$

(ii) $1500 < P \leq 2500$ Psi

$k = -0.11059.10^{-5}\ T^2 + 0.63854.10^{-3}\ T + 0.31182$

(iii) $2500 < P \leq 3500$ Psi

$k = -0.11495.10^{-5}\ T^2 + 0.67117.10^{-3} T + 0.3105.$

(d) CTAGC - It calculates the conductivity (k) of saturated water as a function of temperature (T).

$$k = -0.24173.10^{-5}\ T^2 + 0.99835.10^{-3}\ T + 0.28862$$

for $T \leq 100\ ^{\circ}F$.

$$k = -0.10408.10^{-5}\ T^2 + 0.5628.10^{-3} + 0.32132$$

for $100 < T \leq 400\ ^{\circ}F$.

$$k = -0.20081.10^{-5}\ T^2 + 0.15749.10^{-2}\ T + 0.06624$$

for $T > 400\ ^{\circ}F$

(e) CTMTP - It calculates the conductivity (k) of the material of the tube. The material chosen in this problem is Inconel-718.

$$k = 57.78\ (-1.98x10^{-6}\ T^2 + 8.91x10^{-4}\ T + 0.151)$$

where k is in Btu/hr-ft-$^{\circ}F$ and T in $^{\circ}C$.

(f) FTMDF - It calculates the multiplication factor needed to evaluate two-phase frictional pressure drop. For this Baroczy's plot [9] is used. The X-axis of this log-log plot is divided into 6 regions and the segments in each region is assumed to be linear such that

$$\phi^2_{Lo} = \text{Exp}\ (A + B \ln I).$$

A and B are determined using the plot. The six regions are:

Region I : $0.00001 \leq I \leq 0.001$

Region II : $0.001 < I \leq 0.003$

Region III : $0.003 < I \leq 0.007$

Region IV : $0.007 < I \leq 0.03$

Region V : $0.03 < I \leq 0.1$

Region VI : $0.1 < I \leq 1.0$

where $I = (\mu_l/\mu_v)^{0.2} (\rho_l/\rho_v)$

(g) QFOCV - It calculates F, S and σ to be used in Chen's correlation.

$F = \text{Exp}\,[0.60358 + 0.21681 \ln(X_{tt}^{-1})]$, $0.1 \quad X_{tt}^{-1} \quad 0.2$

$F = \text{Exp}\,[0.94034 + 0.42604 \ln(X_{tt}^{-1})]$, $0.2 \quad X_{tt}^{-1} \quad 0.6$

$F = \text{Exp}\,[1.0359 + 0.61316 \ln(X_{tt}^{-1})]$, $0.6 \quad X_{tt}^{-1} \quad 2.0$

$F = \text{Exp}\,[0.96332 + 0.71791 \ln(X_{tt}^{-1})]$, $2.0 \quad X_{tt}^{-1} \quad 100.0$

$S = 0.43321.10^{-10} B^2 - 0.10254.10^{-4} B + 0.97877$

For $14990 \leq B \leq 10^5$

$S = 0.54595.10^{-11} B^2 - 0.33653.10^{-5} B + 0.65916$

For $10^5 < B \leq 3.0 \times 10^5$

$S = 0.10265.10^{-11} B^2 - 0.99733.10^{-6} B + 0.34334$

For $3 \times 10^5 < B \leq 5 \times 10^5$

$S = 0.11075.10^{-12}\ B^2 - 0.18338.10^{-6}\ B + 0.16406$

For $5x10^5 < B \leq 7x10^5$

$S = 0.9$, For $B > 7x10^5$

where $B = Re_1 . F^{1.25}$

$\sigma = 0.157.10^{-8}\ P^2 - 0.36872.10^{-5}\ P + 0.0033934$

For $P \leq 1000$ Psi

$\sigma = 0.2023.10^{-9}\ P^2 - 0.1402.10^{-5}\ P + 0.0024308$

For $1000 < P \leq 3000$ Psi

where σ is in lbf/ft.

(h) TLSUB - It determines the temperature of compressed water for a given pressure (P, psi) and specific enthalpy (H, Btu/lbm).

$H = 0.26127.10^{-2}\ P + 68.0349$, $T = 100\ ^oF$

$H = 0.22714.10^{-2}\ P + 167.946$, $T = 200\ ^oF$

$H = 0.18834.10^{-2}\ P + 269.445$, $T = 300\ ^oF$

$H = 0.49075.10^{-7}\ P^2 + 0.10506.10^{-2}\ P + 374.7088$, $T = 400\ ^oF$

$H = 0.10528.10^{-6}\ P^2 - 0.56072.10^{-3}\ P + 488.1221$, $T = 500\ ^oF$

$H = 0.81068.10^{-6}\ P^2 - 0.84505.10^{-2}\ P + 628.158,\ T = 600\ ^{o}F$

$H = 0.13558.10^{-5}\ P^2 - 0.13685.10^{-1}\ P + 666.845,\ T = 620\ ^{o}F$

$H = 0.18628.10^{-5}\ P^2 - 0.20086.10^{-1}\ P + 711.776,\ T = 640\ ^{o}F$

$H = 0.53821.10^{-5}\ P^2 - 0.46992.10^{-1}\ P + 794.942,\ T = 660\ ^{o}F$

$H = 0.75397.10^{-5}\ P^2 - 0.7298.10^{-1}\ P + 896.170,\ T = 680\ ^{o}F$

$H = 0.19416.10^{-4}\ P^2 - 0.16793.P + 1104.3,\ T = 690\ ^{o}F$

$H = 0.24845.10^{-4}\ P^2 - 0.22748.P + 1274.58,\ T = 700\ ^{o}F.$

(:) VIAGC - It determines the viscosity (μ) of compressed water in lbm/Hr-ft as a function of pressure (p, psi) and temperature (T, ^{o}F).

(i) $P \leq 1500$ Psi

$\mu = 0.3705.10^{-3}\ T^2 - 0.87236.10^{-1}\ T + 6.6531$

for $T \leq 110\ ^{o}F$

$\mu = -0.66532.10^{-7}\ T^3 + 0.66982.10^{-4}\ T^2 - 0.23742.10^{-1}\ T$

$+3.3519$ for $110\ ^{o}F < T \leq 400\ ^{o}F$

$\mu = 0.14575.10^{-5}\ T^2 - 0.20341.10^{-2}\ T + 0.90965$

for $T > 400\ ^{o}F$

(iii) $1500 < P \leq 2500$ Psi

$$\mu = 0.36496.10^{-3}\ T^2 - 0.86013.10^{-1}\ T + 6.5907,\quad T \leq 110\ ^{\circ}F$$

$$\mu = -0.65878.10^{-7}\ T^3 + 0.66302.10^{-4}\ T^2 - 0.23542.10^{-1}\ T + 3.3435,\quad 110\ ^{\circ}F < T \leq 400\ ^{\circ}F$$

$$\mu = 0.11304.10^{-5}\ T^2 - 0.17363.10^{-2}\ T + 0.84679,\quad T > 400\ ^{\circ}F$$

(iii) $2500 \text{ Psi} < P \leq 3500$ Psi

$$\mu = 0.35894.10^{-3}\ T^2 - 0.84719.10^{-1}\ T + 6.5258,\quad T \leq 110^{\circ}F$$

$$\mu = -0.65076.10^{-7}\ T^3 - 0.65502.10^{-4}\ T^2 - 0.23311.10^{-1}T + 3.3325,\quad 110 < T \leq 400\ ^{\circ}F$$

$$\mu = 0.52496.10^{-6}\ T^2 - 0.11349.10^{-2}\ T + 0.70403,\quad T > 400\ ^{\circ}F$$

(j) VIAGS - It determines the viscosity of saturated water (μ) in lb/Hr-ft as a function of temperature (T).

$$\mu = 0.37664.10^{-3}\ T^2 - 0.88541.10^{-1}\ T + 6.7181,\quad T \leq 110\ ^{\circ}F$$

$$\mu = -0.67639.10^{-7}\ T^3 + 0.68025.10^{-4}\ T^2 - 0.24029.10^{-1}\ T + 3.3665,\quad 110^{\circ}F < T \leq 400^{\circ}F$$

$$\mu = 0.29905.10^{-6}\ T^2 - 0.87608.10^{-3}\ T + 0.62286,\quad T > 400^{\circ}F$$

(k) VIVAS - It calculates the viscosity of saturated vapour in lbm/Hr-ft as a function of pressure (psi).

$$\mu = 1.15826(-0.24353.10^{-8}\ P^2 + 0.13778.10^{-4}\ P + 0.029109)$$

4.3 Transient calculation:

The details of the computer programme developed for simulating the transients of the steam generator has been discussed in the next section.

4.3.1 Flow chart:

The logic of the program is presented in the form of a flow diagram in figure 4.2.

4.3.2 Subroutines:

(a) SOLUC - This subroutine calls a few other subroutines and simulates the transients. The function of this subroutine is given in the form of a flow diagram in figure 4.3.

(b) DPRER - It determines $(\frac{\partial P}{\partial \rho})_u$ for both compressed and saturated water. To evaluate this the following relationship is made use of.

$$\left(\frac{\partial P}{\partial \rho}\right)_u = -\frac{1}{\rho^2}\left(\frac{\partial P}{\partial v}\right)_u$$

(i) Compressed water:

For compressed water the specific volume (v) was expressed as a function of internal energy (u) at different pressures using the data from the compressed water table of Ref. 11. The polynomials are of the form

$$v = a + bu + cu^2$$

where a, b and c are:

Pressure (Psi)	a	b	c
400.0	0.15991E-01	0.90211E-06	0.16408E-07
600.0	0.15979E-01	0.92847E-06	0.16303E-07
800.0	0.15987E-01	0.40455E-06	0.17907E-07
1000.0	0.15974E-01	0.46761E-06	0.17698E-07
1500.0	0.15945E-01	0.58317E-06	0.17275E-07
2000.0	0.16044E-01	-0.20277E-05	0.23350E-07
2500.0	0.16176E-01	-0.44908E-05	0.27727E-07
3000.0	0.16503E-01	-0.93308E-05	0.35265E-07

To evaluate the required derivative the range of pressure between which the known pressure exists is first determined. Let us assume that the lower limits is P_{lo} and upper limit is P_u. Corresponding to these two pressures the specific volumes v_{lo} and v_u are determined using the appropriate polynomial. The required derivative will be

$$\left(\frac{\partial P}{\partial \rho}\right)_u = \frac{P_{lo} - P_u}{-^2 (v_{lo} - v_u)}$$

(ii) Saturated water:

For saturated water two other pressures are selected such that they are on either side of the known pressure, equidistant from the known pressure and do not differ very much from the known pressure. At these two pressures the

specific volumes and hence the densities are determined and then the required derivative is calculated by expressing it in finite difference form.

The error introduced by this technique is partly due to the fact that the slope of the chord differs slightly from the slope of the tangent at the mid-point of the arc, and partly due to the small difference between adjacent variables.

(c) DPREU - This subroutine determines $(\frac{\partial P}{\partial u})_\rho$. The technique followed in this subroutine is same as that described for the subroutine DPRER. But in this case the internal energy (u) is expressed as a function of specific volume (v) for the compressed water. The polynomials are of the form

$$u = a + bv + c\,v^2$$

where a, b and c are:

Pressure (Psi)	a	b	c
400.0	- 0.14297E+05	0.15499E+07	- 0.40931E+08
600.0	- 0.14353E+05	0.15575E+07	- 0.41179E+08
800.0	- 0.82765E+04	0.84810E+06	- 0.20534E+08
1000.0	- 0.83259E+04	0.85421E+06	- 0.20716E+08
1500.0	- 0.84463E+04	0.86913E+06	- 0.21161E+08
2000.0	- 0.47179E+04	0.45091E+06	- 0.95155E+07

2500.0	- 0.34271E+04	0.31700E+06	- 0.61180E+07
3000.0	- 0.25488E+04	0.22901E+06	- 0.39811E+07

(d) NEWTON - This subroutine determines the quality of steam using Newton-Rapshon's method. It utilizes the following four polynomials which are obtained by fitting curves for the saturation pressure of water. The following polynomials are valid in the range $401.7 \leq P \leq 2532.4$ psi.

$$v_f = 0.1745921\text{x}10^{-1} + 0.5229798\text{x}10^{-5}\ P - 0.1625896\text{x}10^{-8}\ P^2 + 0.5351606\text{x}10^{-12}\ P^3.$$

$$v_g = 0.1967797\text{x}10^{+1} - 0.2710660\text{x}10^{-2}\ P + 0.1436388\text{x}10^{-5}\ P^2 - 0.2599688\text{x}10^{-9}\ P^3.$$

$$u_f = 0.3178337\text{x}10^{3} + 0.3054259\ P - 0.1020149\text{x}10^{-3}\ P^2 + 0.1756466\text{x}10^{-7}\ P^3.$$

$$u_g = 0.1120552\text{x}10^{4} + 0.4207413\text{x}10^{-2}\ P - 0.1494585\text{x}10^{-4}\ P^2 - 0.4154948\text{x}10^{-9}\ P^3$$

The quality $X = \dfrac{u - u_f}{u_g - u_f} = \dfrac{v - v_f}{v_g - v_f}$

i.e., $u(v_g - v_f) - v(u_g - u_f) + u_g v_f - u_f v_g = 0$

In the L.H.S. of this expression u and v are known and hence constant. All variables other than these two are function of pressure. So pressure can be calculated from this equation. For this purpose Newton-Rapshon's method is used. Once pressure is known u_f and u_g can be calculated from the above polynomials and hence the quality X can be determined.

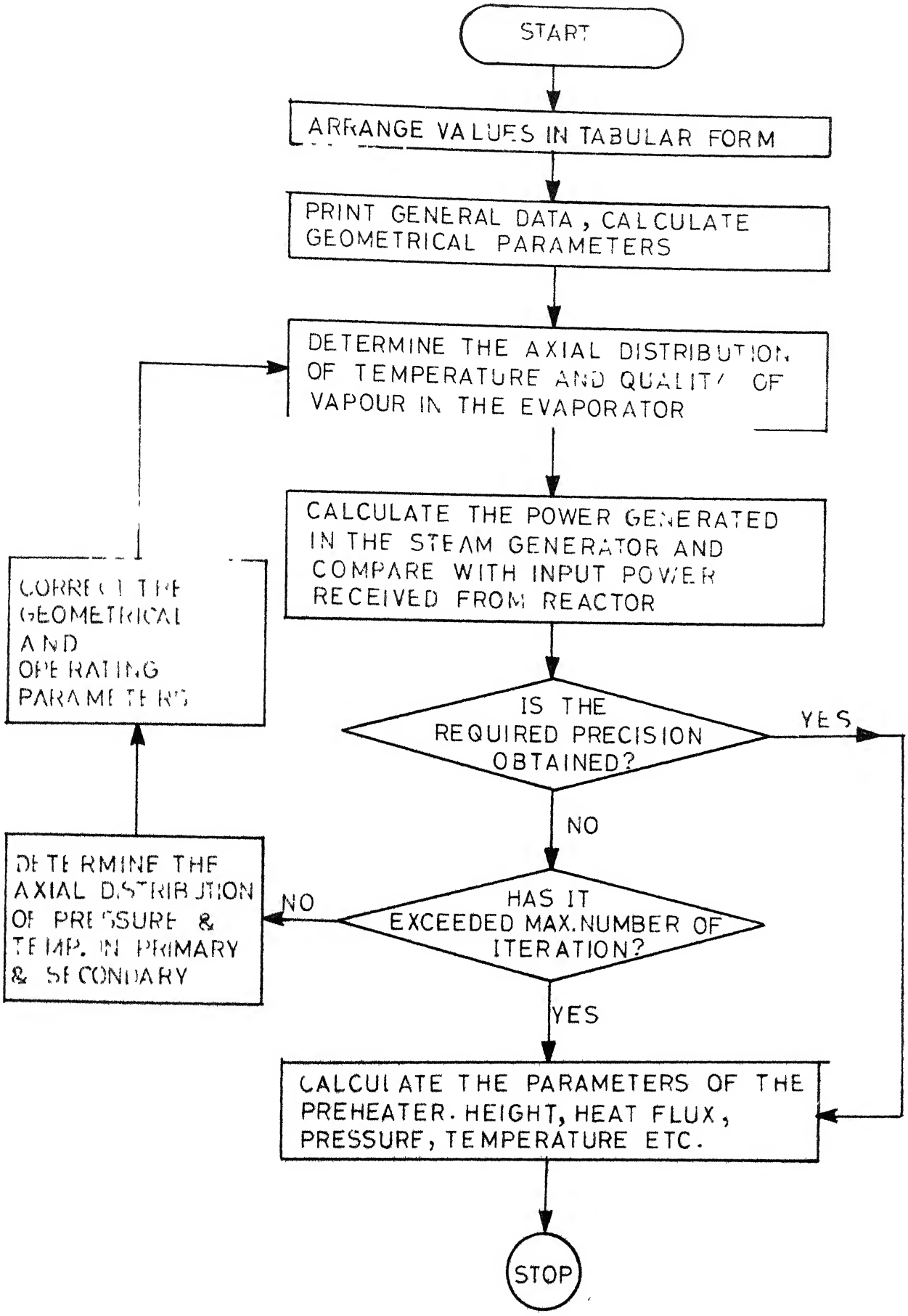
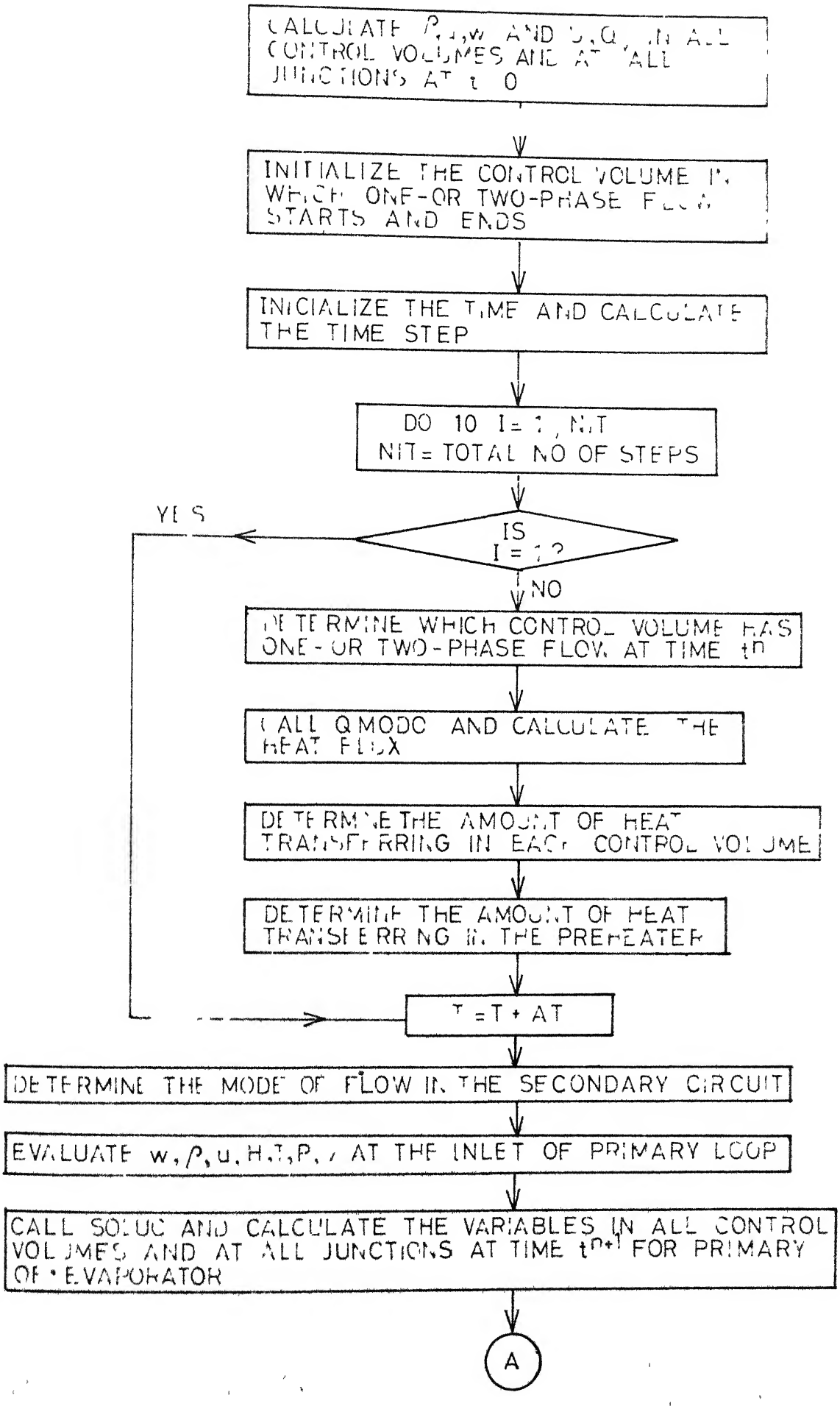
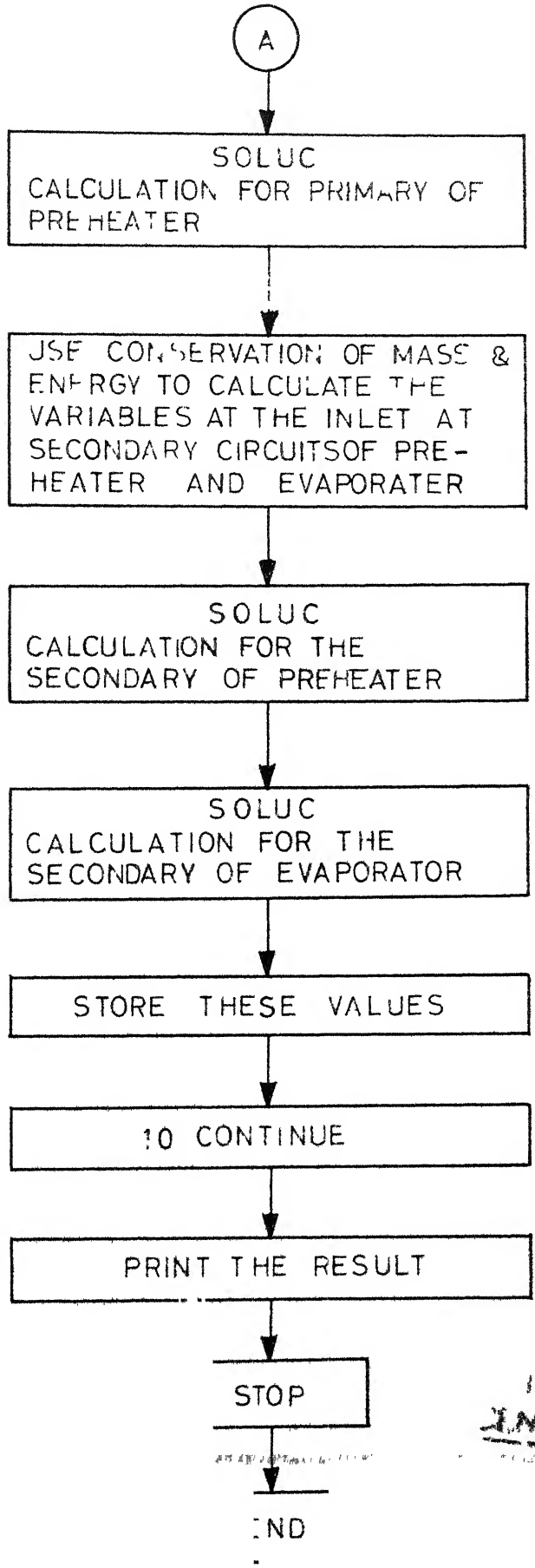
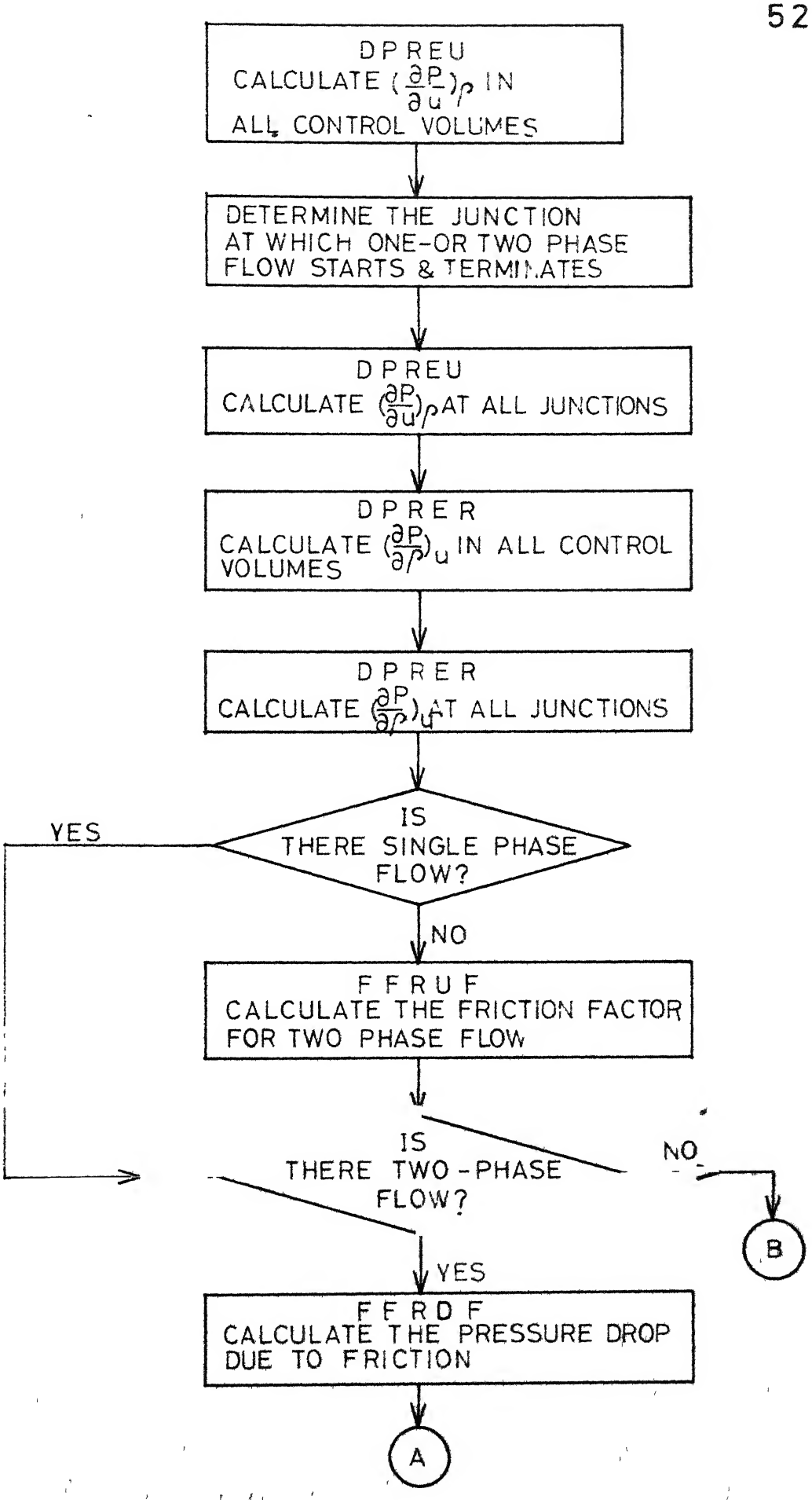


Fig. 4·1 Flow chart of the computer programme calculating the steady state values


CALCULATE P, u, w AND U, Q, IN ALL CONTROL VOLUMES AND AT ALL JUNCTIONS AT t = 0
INITIALIZE THE CONTROL VOLUME IN WHICH ONE-OR TWO-PHASE FLOW STARTS AND ENDS
INICIALIZE THE TIME AND CALCULATE THE TIME STEP
DO 10 I = 1, NIT
NIT= TOTAL NO OF STEPS
YES
IS I = 1 ?
NO
DETERMINE WHICH CONTROL VOLUME HAS ONE-OR TWO-PHASE FLOW AT TIME tn
CALL QMODC AND CALCULATE THE HEAT FLUX
DETERMINE THE AMOUNT OF HEAT TRANSFERRING IN EACH CONTROL VOLUME
DETERMINE THE AMOUNT OF HEAT TRANSFERRING IN THE PREHEATER
T = T + ΔT
DETERMINE THE MODE OF FLOW IN THE SECONDARY CIRCUIT
EVALUATE w, P, u, H.T, P, / AT THE INLET OF PRIMARY LOOP
CALL SOLUC AND CALCULATE THE VARIABLES IN ALL CONTROL VOLUMES AND AT ALL JUNCTIONS AT TIME t^(n+1) FOR PRIMARY OF EVAPORATOR
A




DPREU
CALCULATE $(\frac{\partial P}{\partial u})_\rho$ IN ALL CONTROL VOLUMES
DETERMINE THE JUNCTION AT WHICH ONE-OR TWO PHASE FLOW STARTS & TERMINATES
DPREU
CALCULATE $(\frac{\partial P}{\partial u})_\rho$ AT ALL JUNCTIONS
DPRER
CALCULATE $(\frac{\partial P}{\partial \rho})_u$ IN ALL CONTROL VOLUMES
DPRER
CALCULATE $(\frac{\partial P}{\partial \rho})_u$ AT ALL JUNCTIONS
IS THERE SINGLE PHASE FLOW?
YES
NO
FFRUF
CALCULATE THE FRICTION FACTOR FOR TWO PHASE FLOW
IS THERE TWO-PHASE FLOW?
NO
B
YES
FFRDF
CALCULATE THE PRESSURE DROP DUE TO FRICTION
A

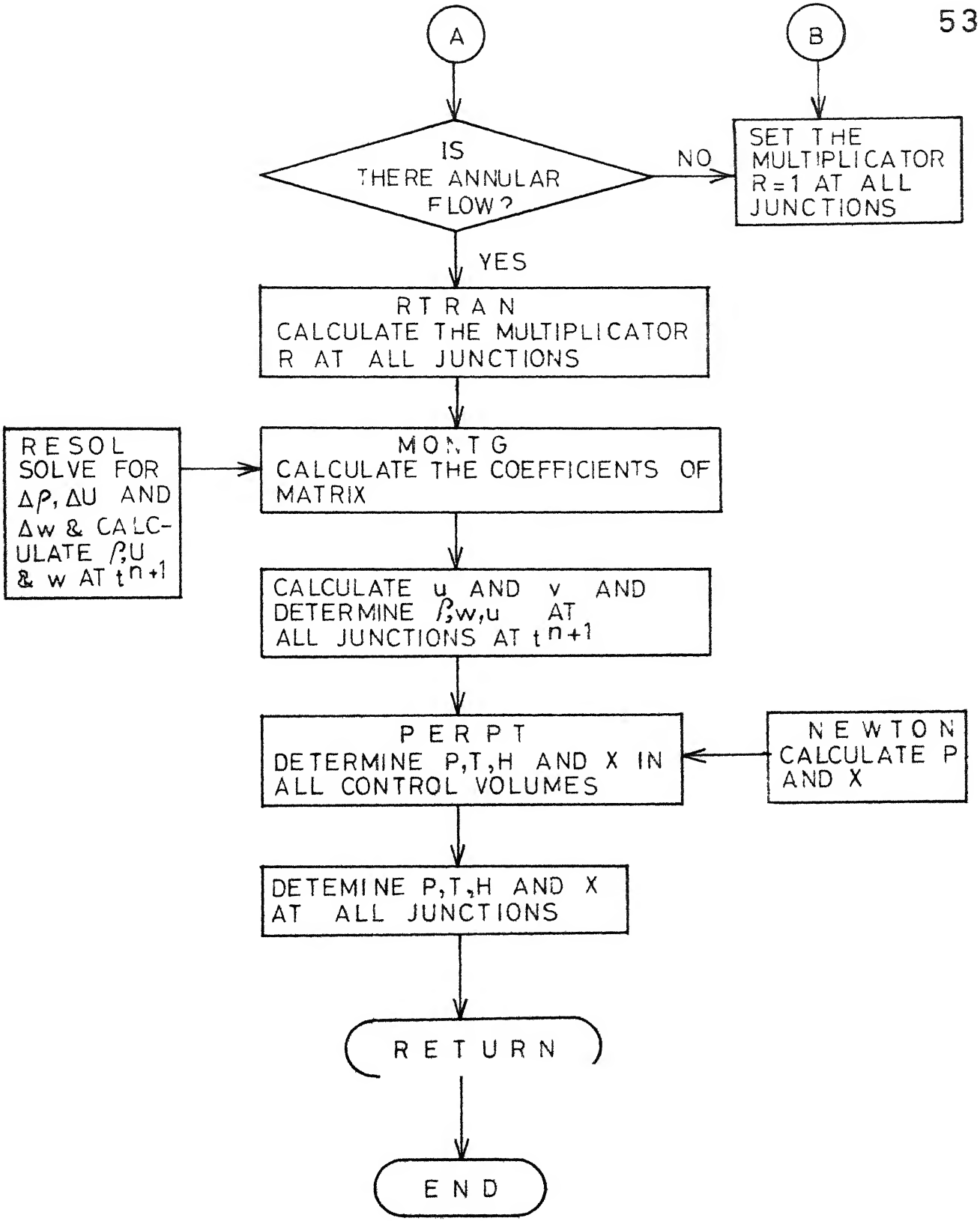


Fig. 4-3 Flow chart of the subroutine SOLUC

CHAPTER 5

RESULTS

5.1 Results and Discussions:

This chapter deals with the results obtained using the computer code developed in this present work. The results will be discussed in details in the following two sections.

5.1.1 Steady state values:

The steady state values which are required for transient analysis were obtained using the computer code developed by A.C. Pinto [7]. These steady state operating values which ibolize the steam generator chosen for transient analysis in the present work are given in appendix C.

5.1.2 Transient values:

The results of the transient analysis are represented in graphical forms. Figures 5.1a through 5.6d indicate the transient behaviour of the steam generator under perturbed conditions.

Figures 5.1a through 5.1d represent the change of variables at the exist of the evaporator of the secondary circuit due to a 5.0 % increment in the mass flow rate at the inlet of the primary circuit. This increase in mass flow rate in the primary circuit will enhance the heat transfer from the primary to the secondary circuit. So the temperature in the secondary circuit

will increase and this will raise the quality. Increase in quality means that there is more vapour and the mass flow rate of vapour is higher. Thus the pressure will rise because there is more vapor and the total mass (liquid and vapor) flow rate will increase.

Figures 5.2a through 5.2d indicate the effect of reducing pressure by 30.0 % at the inlet of the primary circuit. When pressure is reduced by such a large value there will be two-phase flow in the primary circuit and this will increase the heat transfer coefficient from the bulk of the fluid to the tube wall. This essentially will lead to an increase in heat transfer to the secondary circuit and thus the same phenomena as in figures 5.1a through 5.1d will occur.

In figures 5.3a through 5.3d the effect of increasing the internal energy of the primary liquid by 5.0 % has been shown. Since the internal energy of the primary liquid is high, its heat content will also be high and thus the heat transfer from the primary to the secondary circuit will increase. So a similar effect like figures 5.1a through 5.2d can be observed.

Figures 5.4a through 5.4d represent the effect of reducing feed water flow rate by 5 % at the inlet of the secondary circuit. Since the flow rate is reduced in the secondary loop the amount of water receiving heat from the primary circuit is less. So the water in the secondary circuit will have higher

temperature and the quality will increase. Thus there will be an increase in pressure and flow rate. But the disturbance is very small, only 5.0 %. So these changes at the variables at the exit of the evaporator of the secondary circuit will also be very small.

Figures 5.5a through 5.5d indicate the effect of reducing pressure by 30.0 % at the inlet of the secondary circuit. The reduction in pressure will increase the quality and hence the mode of flow of the fluid in the secondary loop will be such that the heat transfer coefficient from the tube wall to the bulk of the fluid will increase which means an increased heat transfer rate. So the temperature will rise which in turn will affect the quality and this increase in quality will increase the pressure and mass flow rate.

Figures 5.6a through 5.6d indicate the effect of increasing the internal energy of the secondary liquid by 5.0 %. This increases the total heat content of the secondary fluid and hence the same phenomena as in figures 5.5a through 5.5d can be observed.

5.2 Conclusions:

In the present study it has been found that a 5.0 % change in the feed water flow rate at the entrance of the secondary circuit of the evaporator does not affect the function of the

steam generator very much. This trend was established by A.C. Pinto [7] in his attempt to find out how the steady state values at the exit of evaporator of the secondary circuit vary due to different feed water flow rates.

In all other cases the change in the variables at the outlet of the evaporator of thessecondary circuit for some disturbances at the inlet conditions is large. This signifies that the mass flow rate, pressure and internal energy at the inlet of the primary circuit and the pressure and internal energy at the entrance of the secondary circuit play an important role in the operation of the steam generator.

If one examines the graphs carefully one will find that there are discontinuities in almost all the graphs at 0.4 sec. This may be due to numerical instability. The time step chosen for the present work is 0.001 sec. So further investigation can be made with reduced time step though this will take more of computer time.

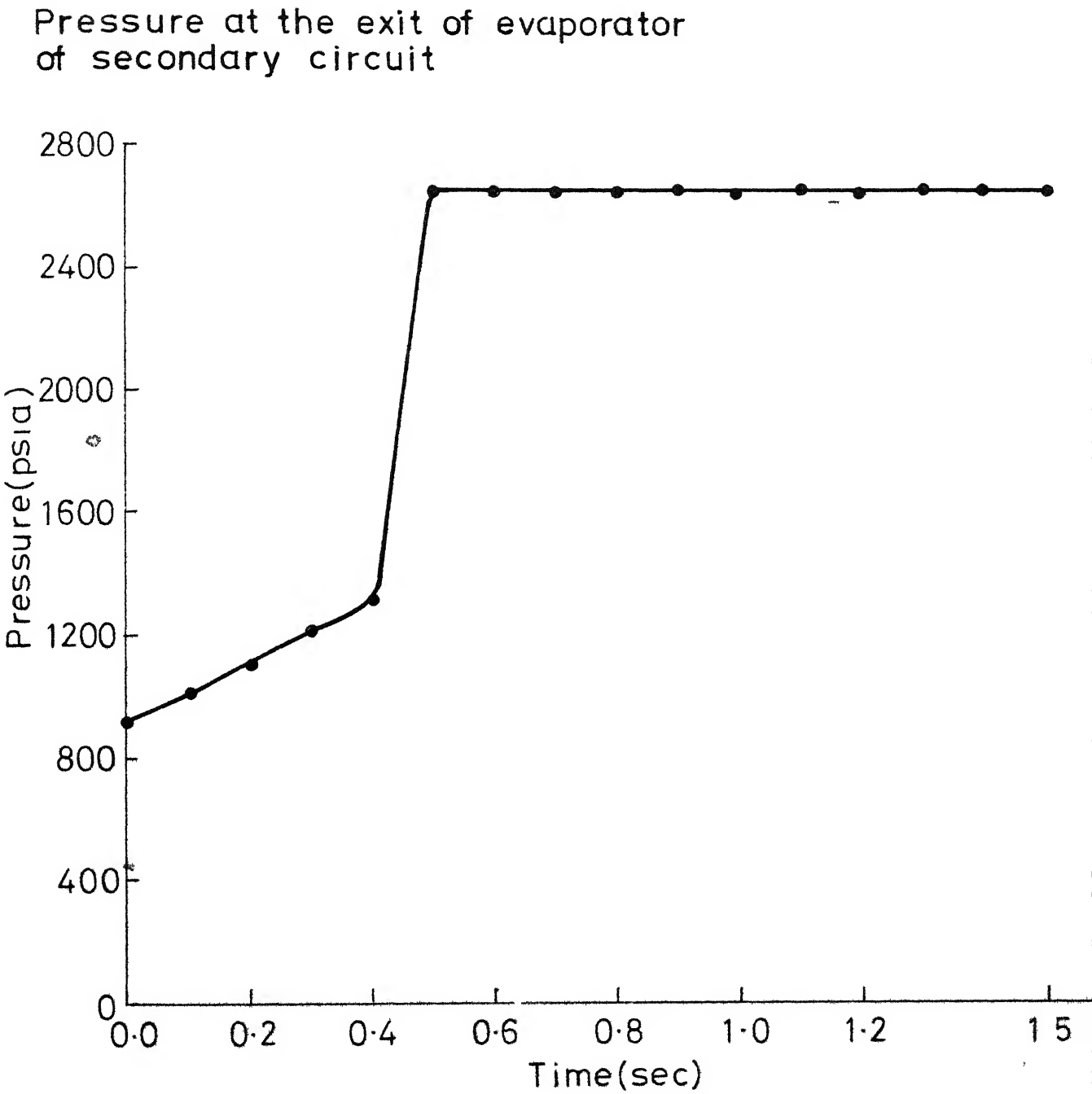


Fig. 5·1a Mass flow rate at the inlet of primary circuit was increased by 5·0%

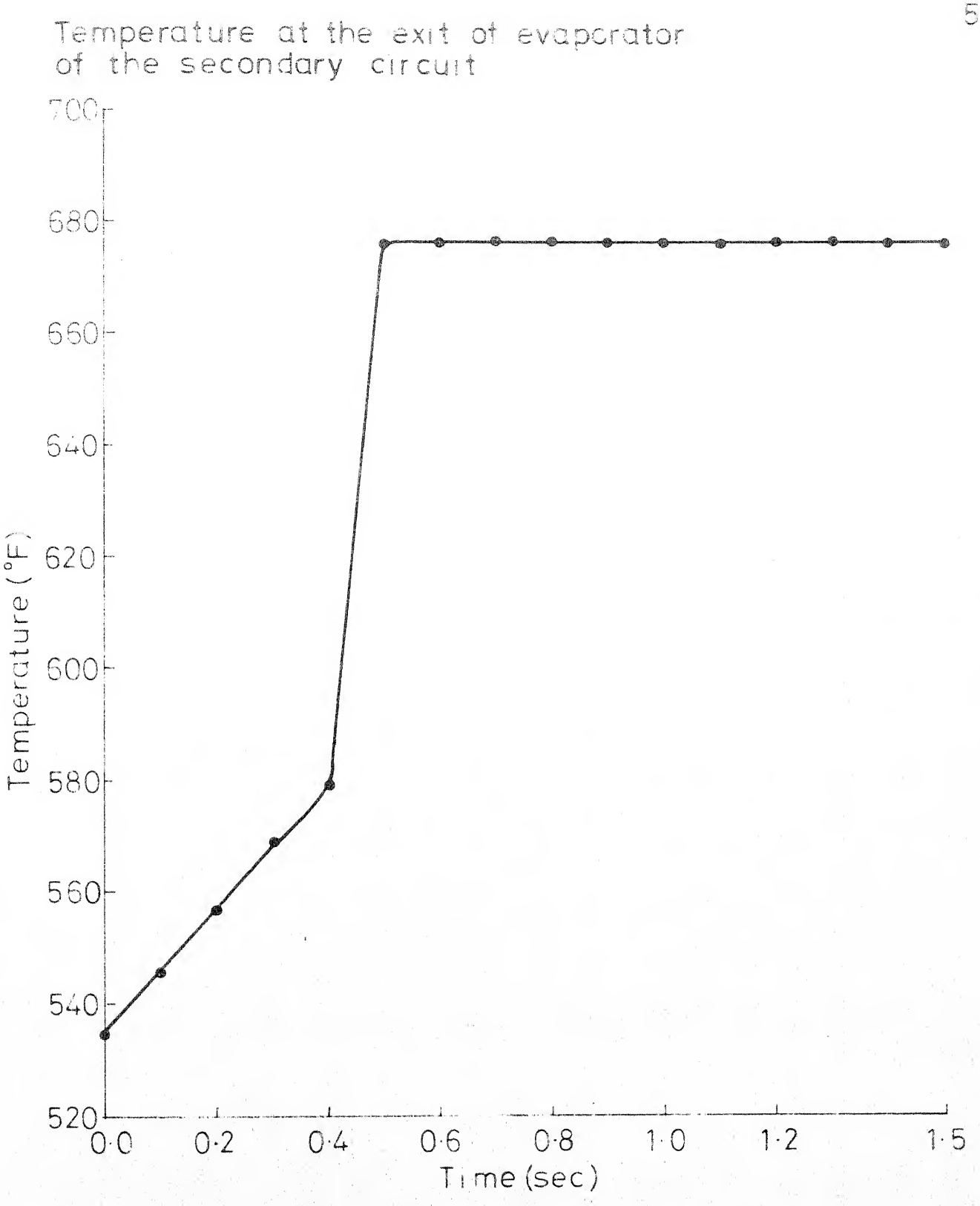


Fig. 5·1b Mass flow rate at the inlet of primary circuit was increased by 5·0%

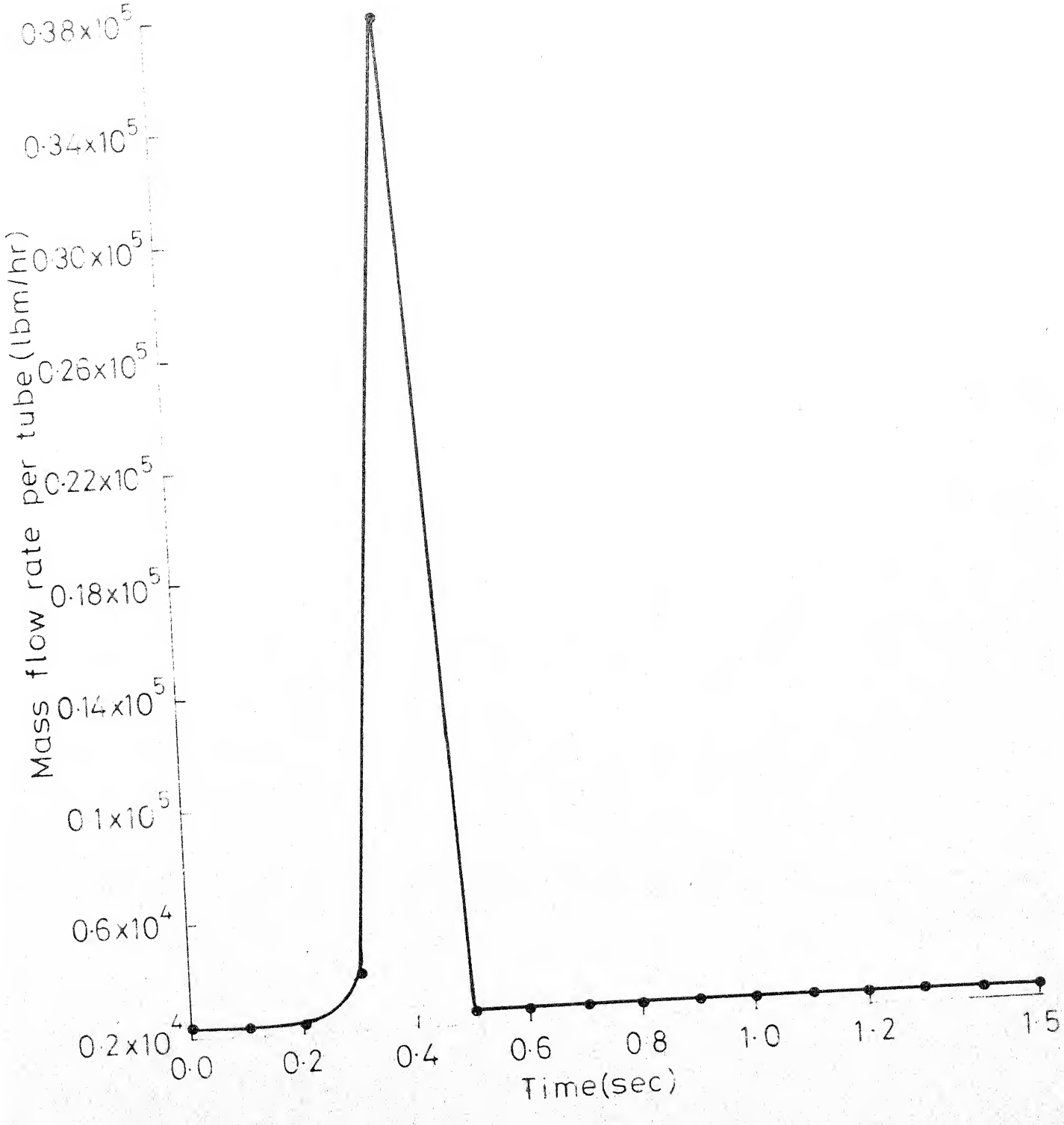


Fig. 5·1c Mass flow rate at the inlet of primary circuit was increased by 5·0%

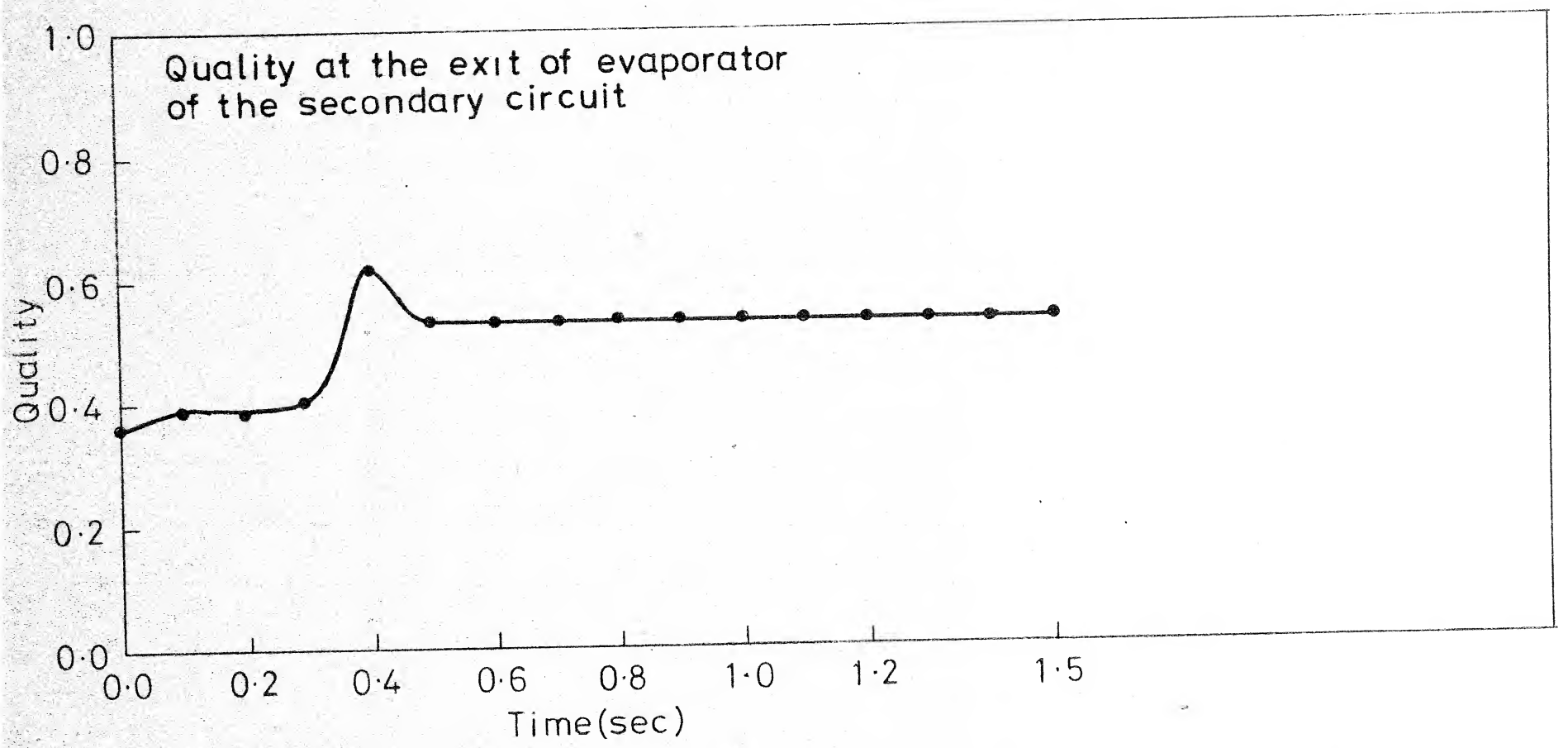


Fig. 5·1d Mass flow rate at the inlet of the primary circuit was increased by 5·0%

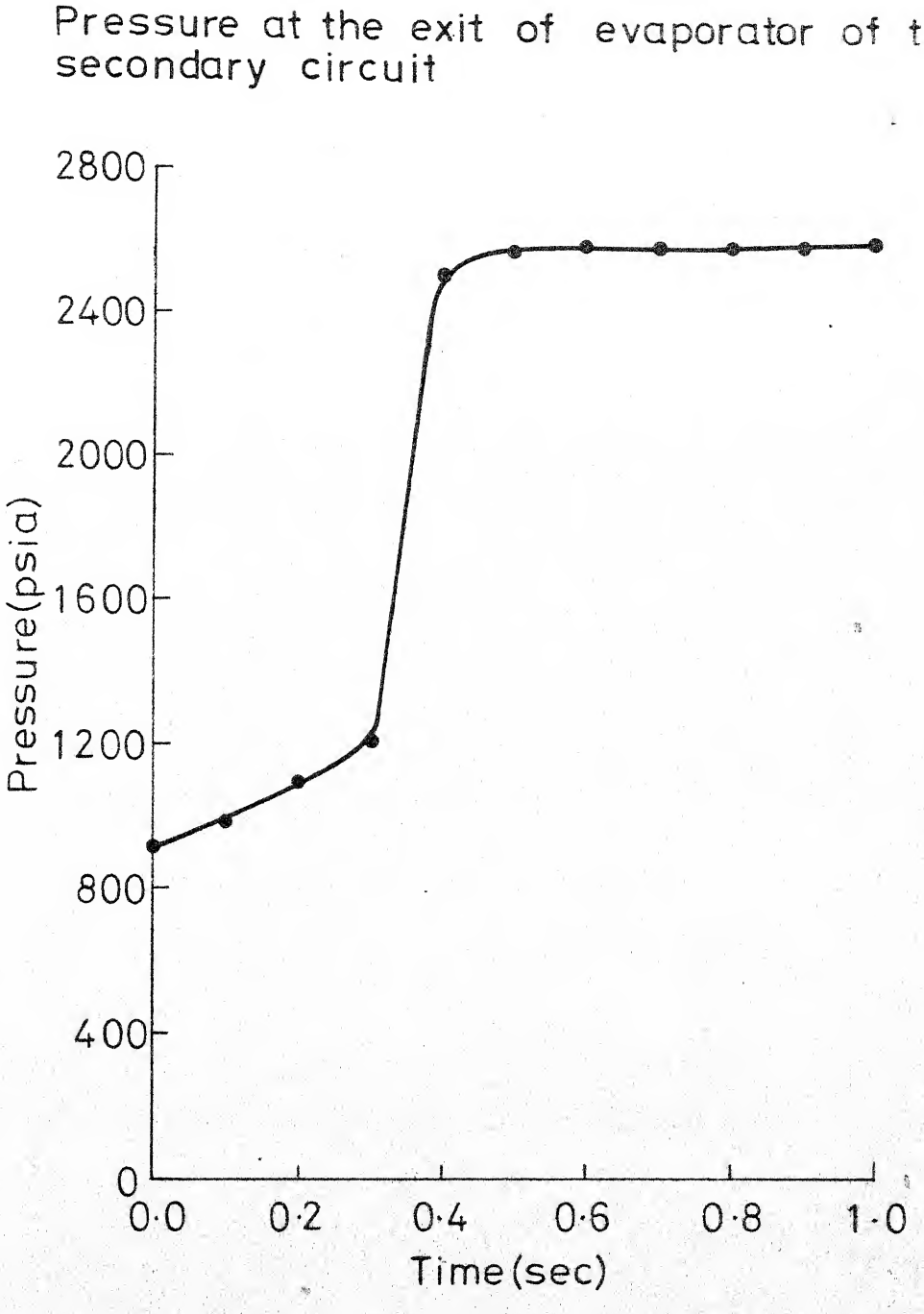


Fig. 5·2a The pressure was reduced by 30% at the entrance of evaporator of the primary circuit

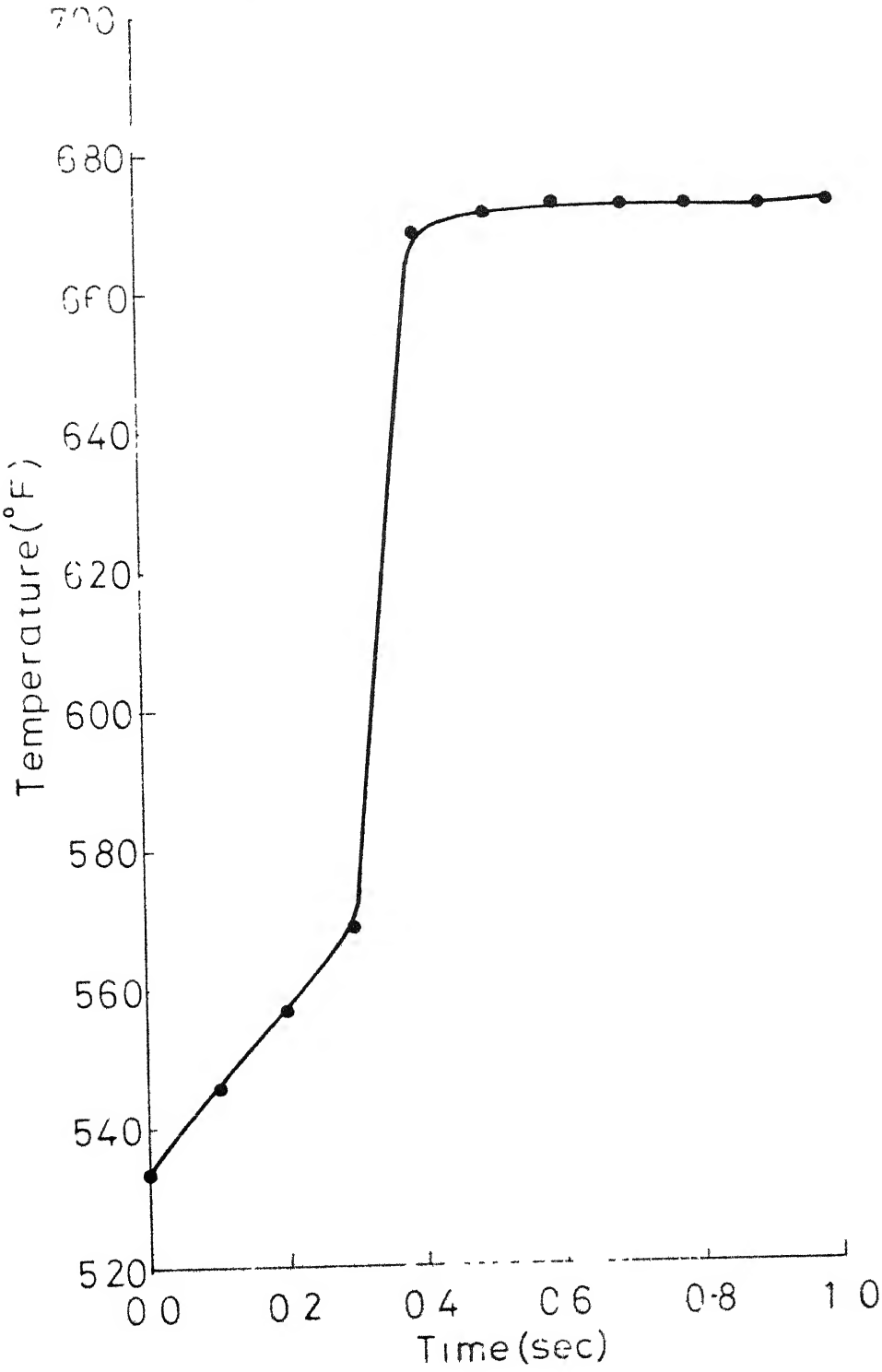


Fig 5·2b The pressure was reduced by 30% at the entrance of evaporator of the imary circuit

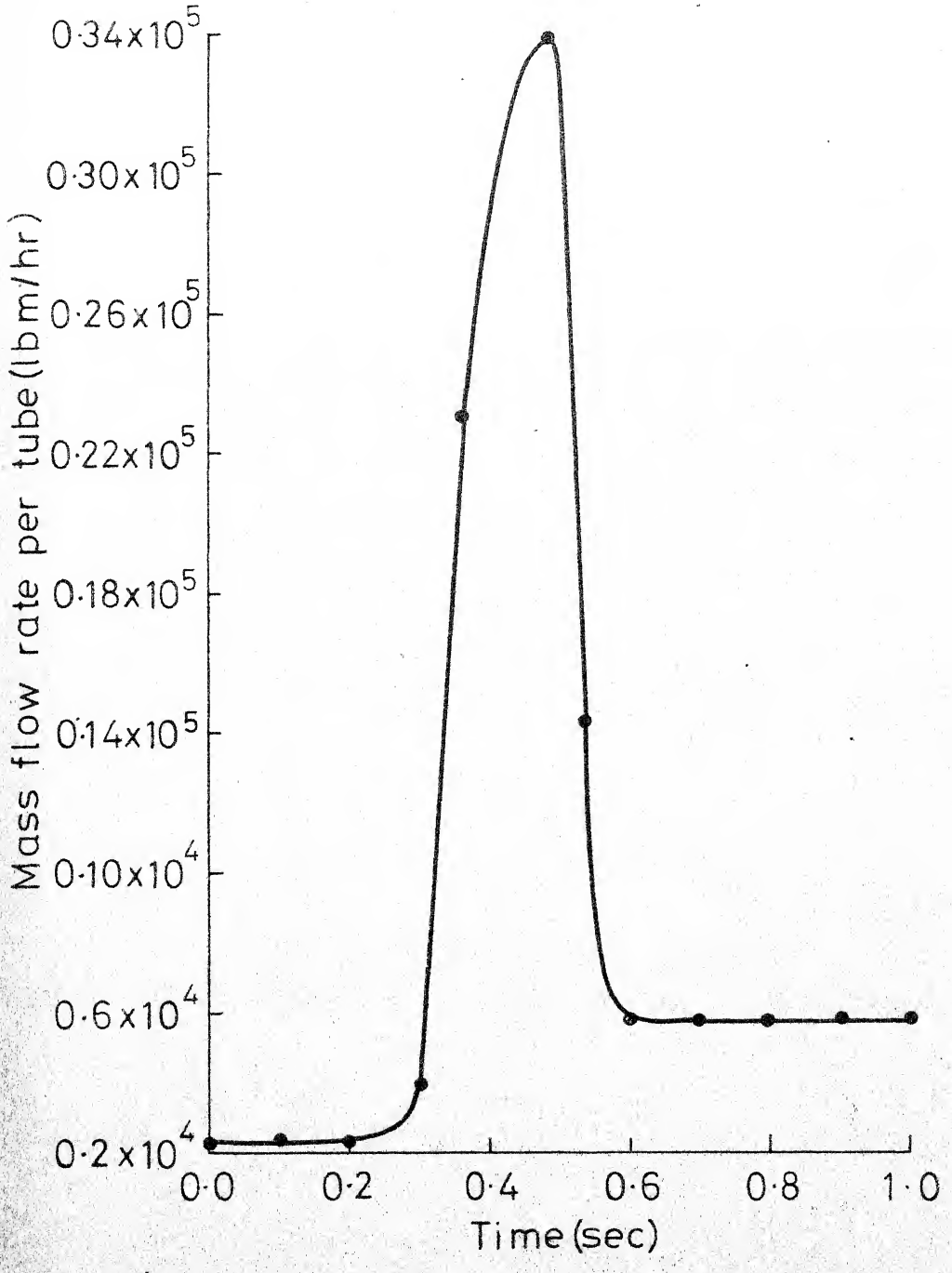


Fig. 5·2c The pressure at the inlet of evaporator of the primary circuit was reduced by 30·0%

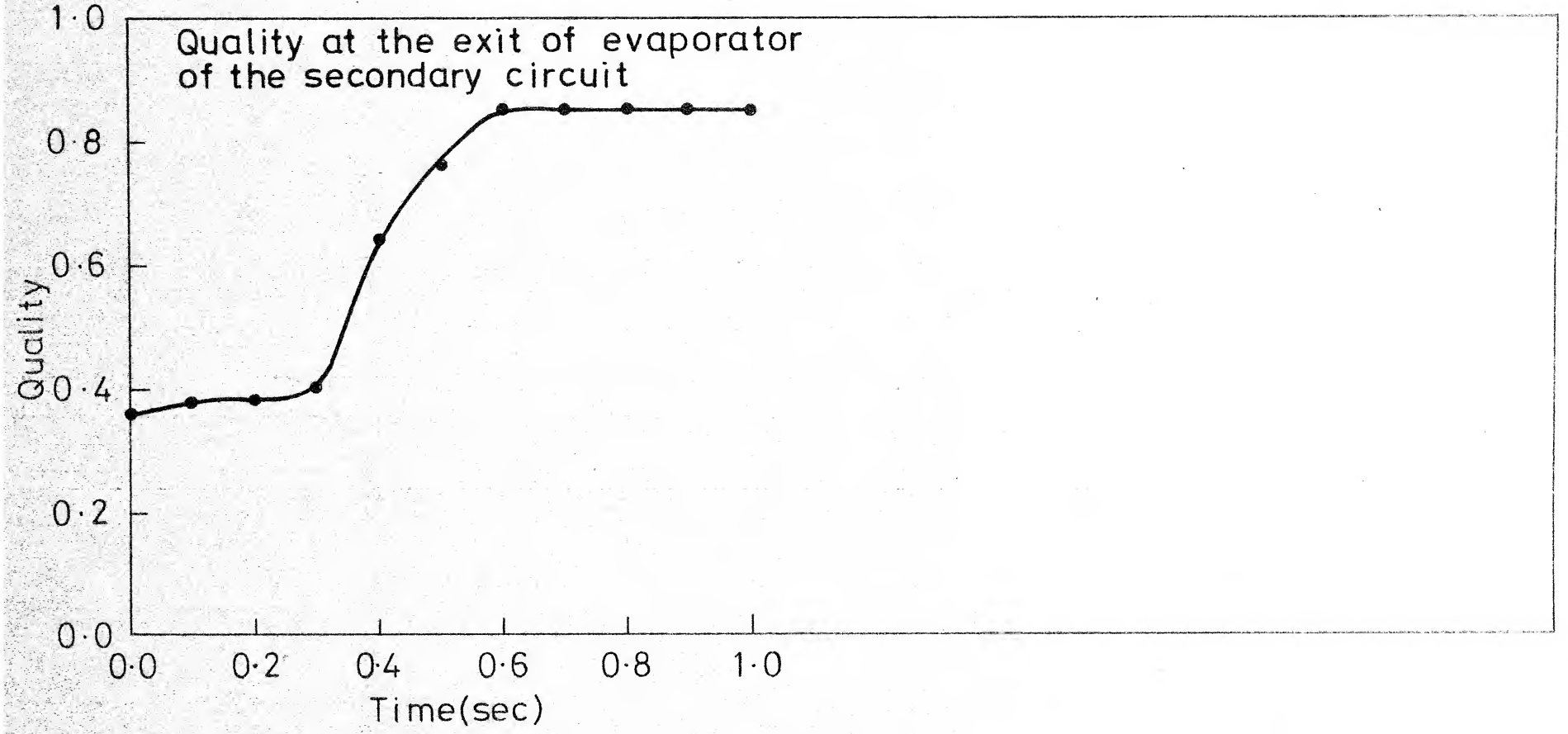


Fig. 5·2d Pressure was reduced by 30·0% at the inlet of evaporator of the primary circuit

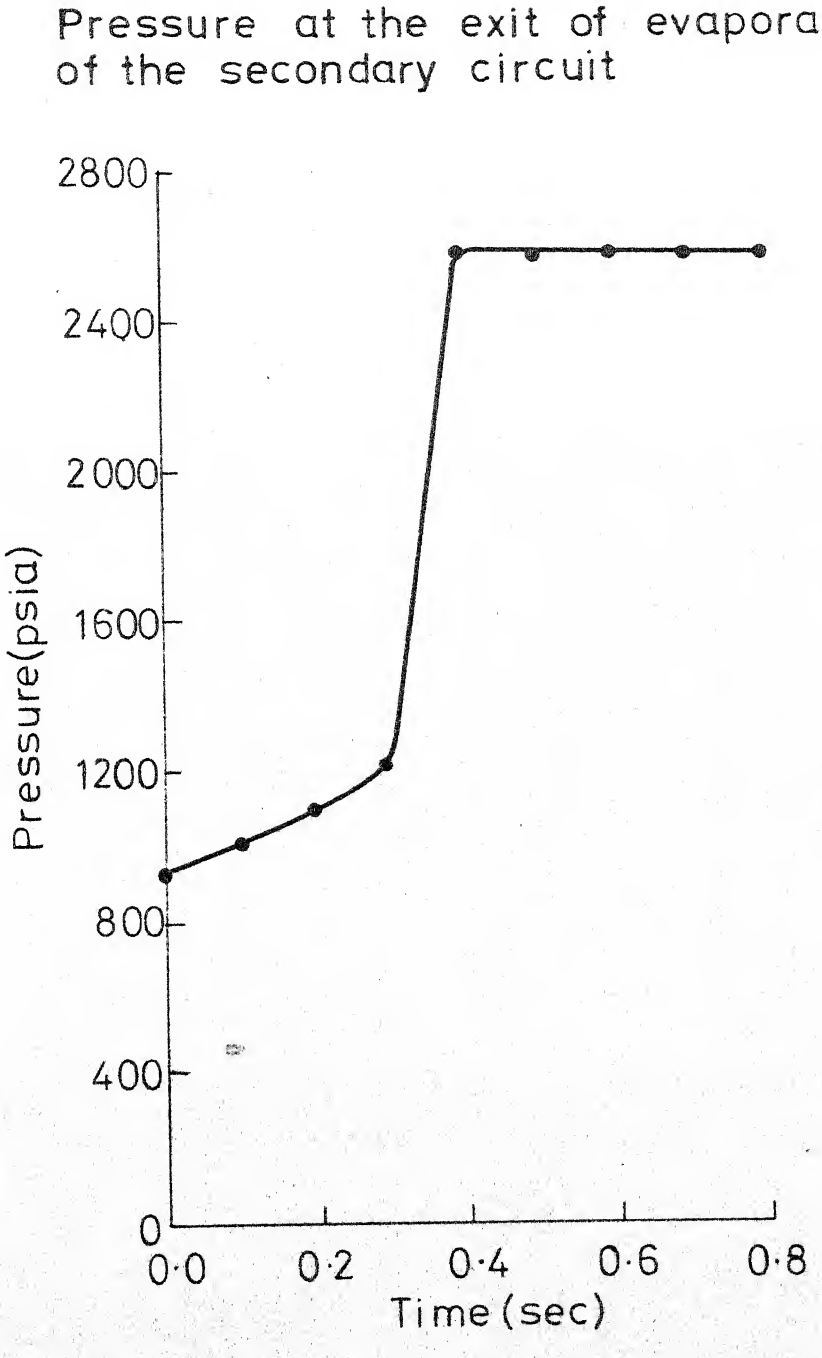


Fig. 5·3a The internal energy of the primary liquid was increased by 5·0% at the entrance of the evaporator

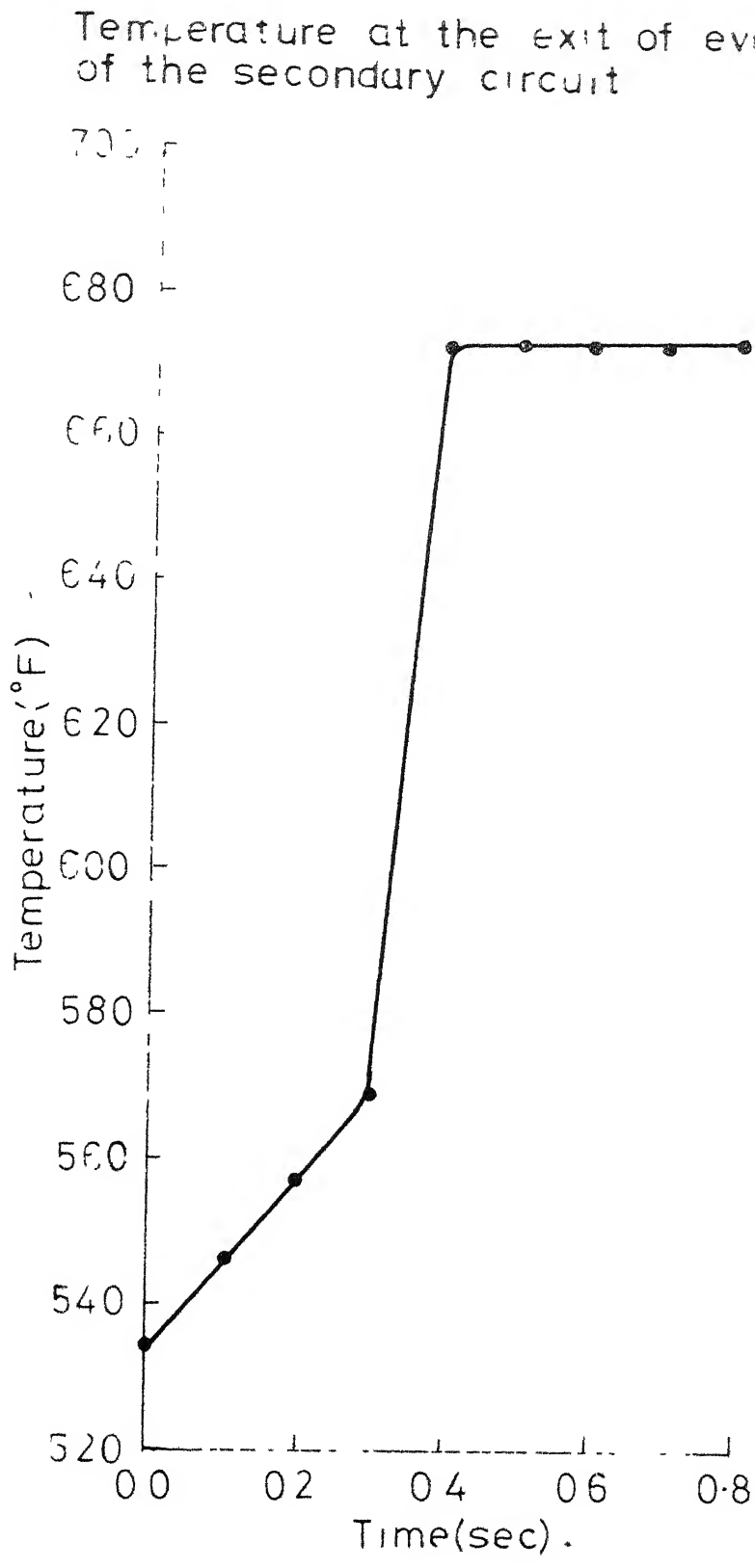


Fig. 5·3b The internal energy of the primary was increased by 5·0% at the inlet of the evaporater

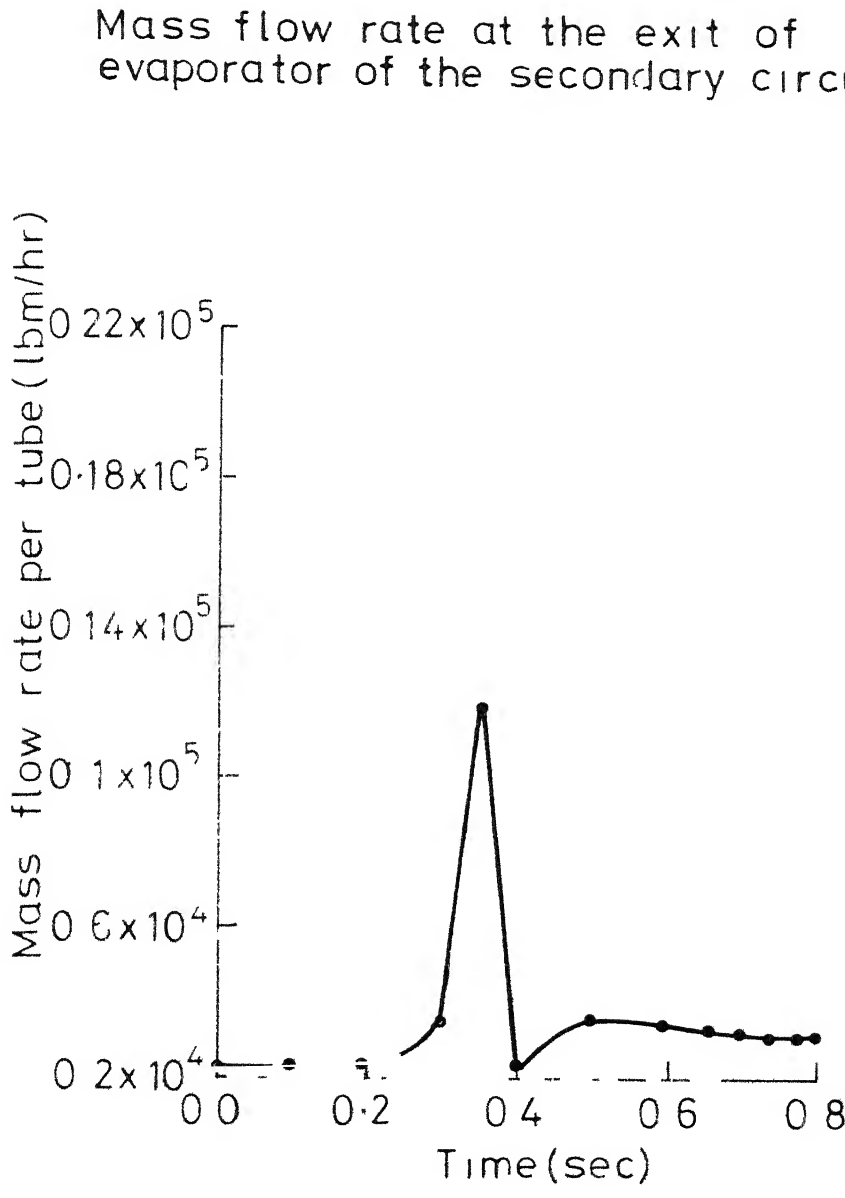


Fig. 5·3c The internal energy of primary liquid was increased by 5·0% at the entrance of the evaporator

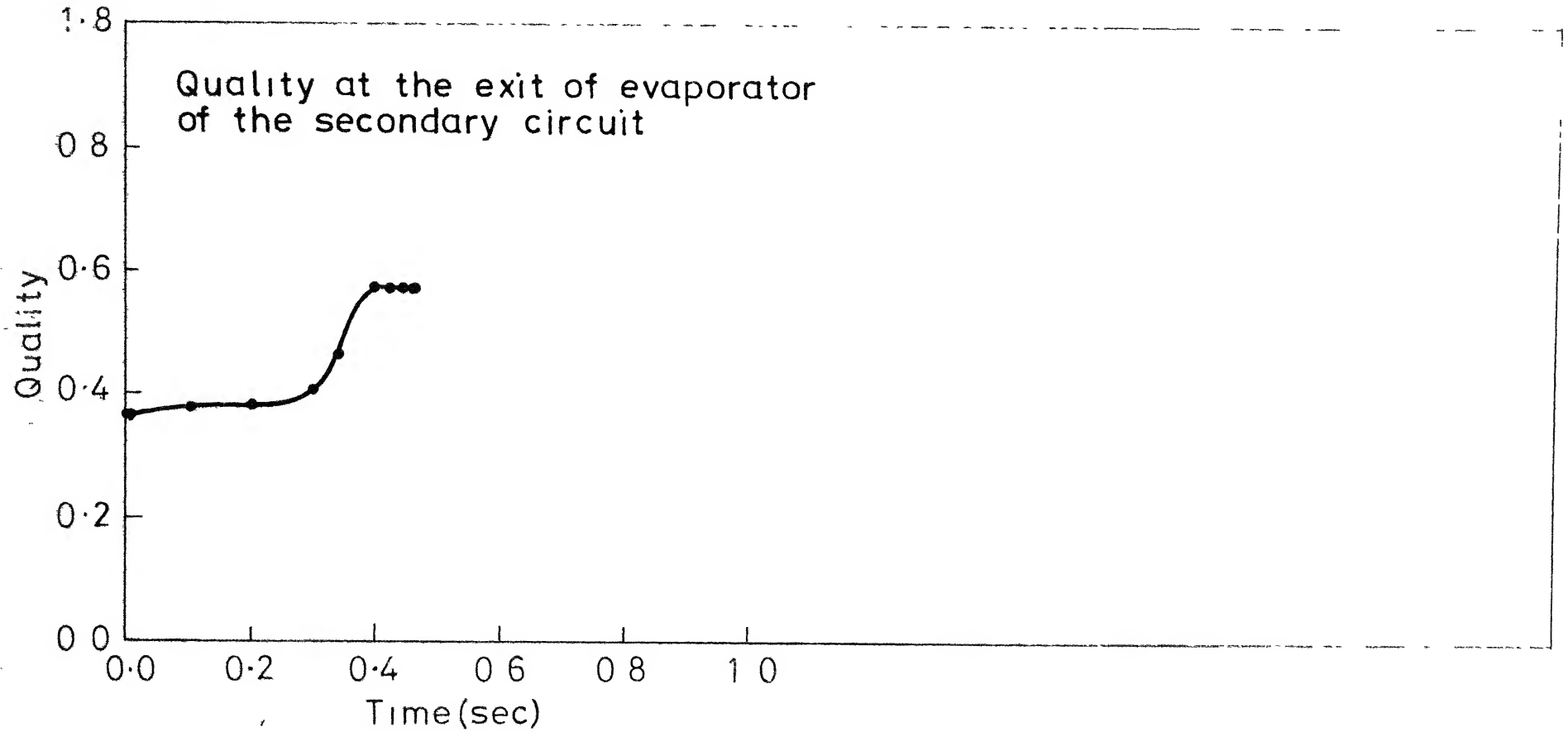


Fig. 5·3d The internal energy of primary liquid was increased by 5·0% at the entrance of the evaporator

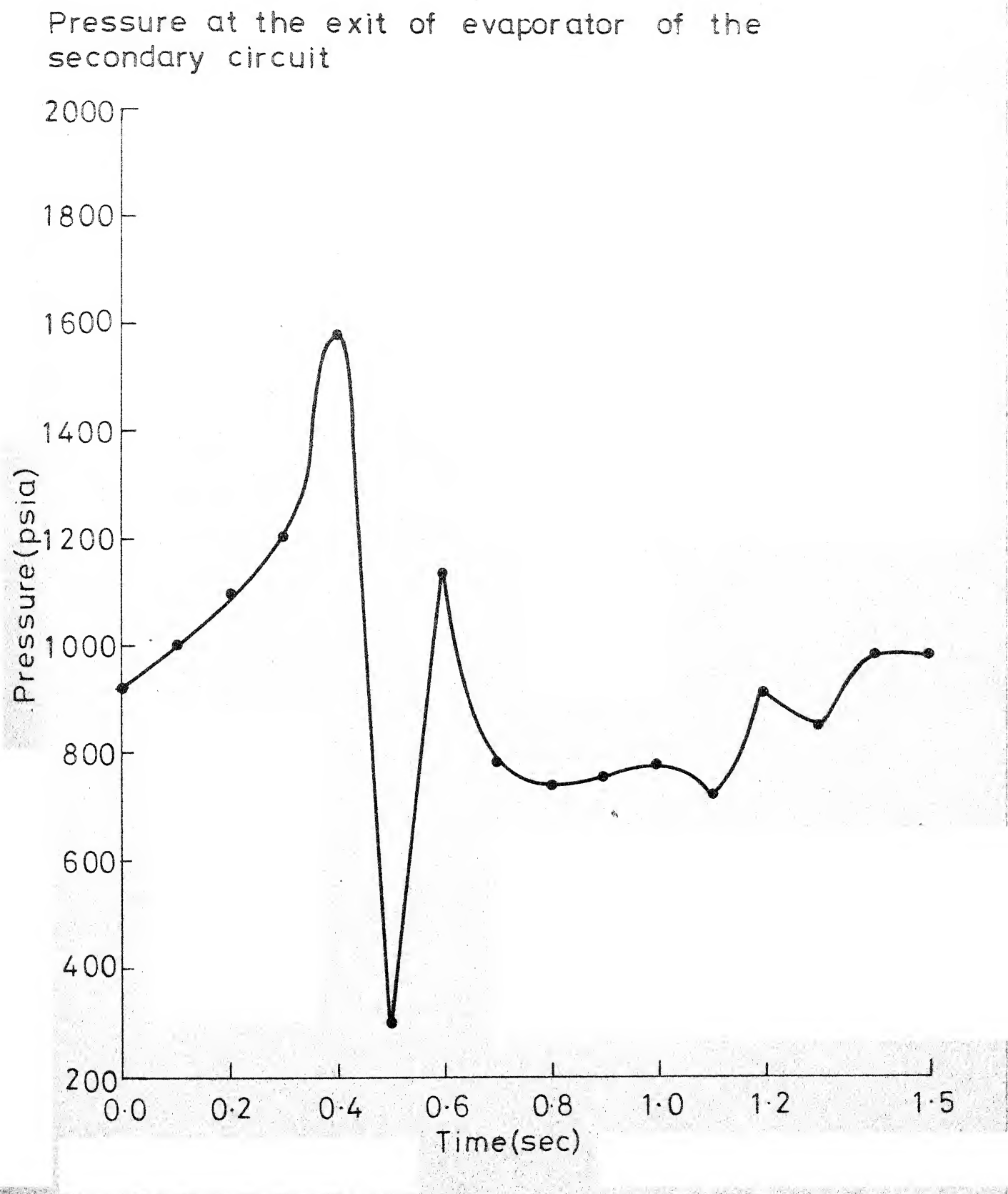


Fig. 5·4a Mass flow rate at the inlet of the secondary circuit was reduced by 5·0%

Temperature at the exit of evaporator of the secondary circuit

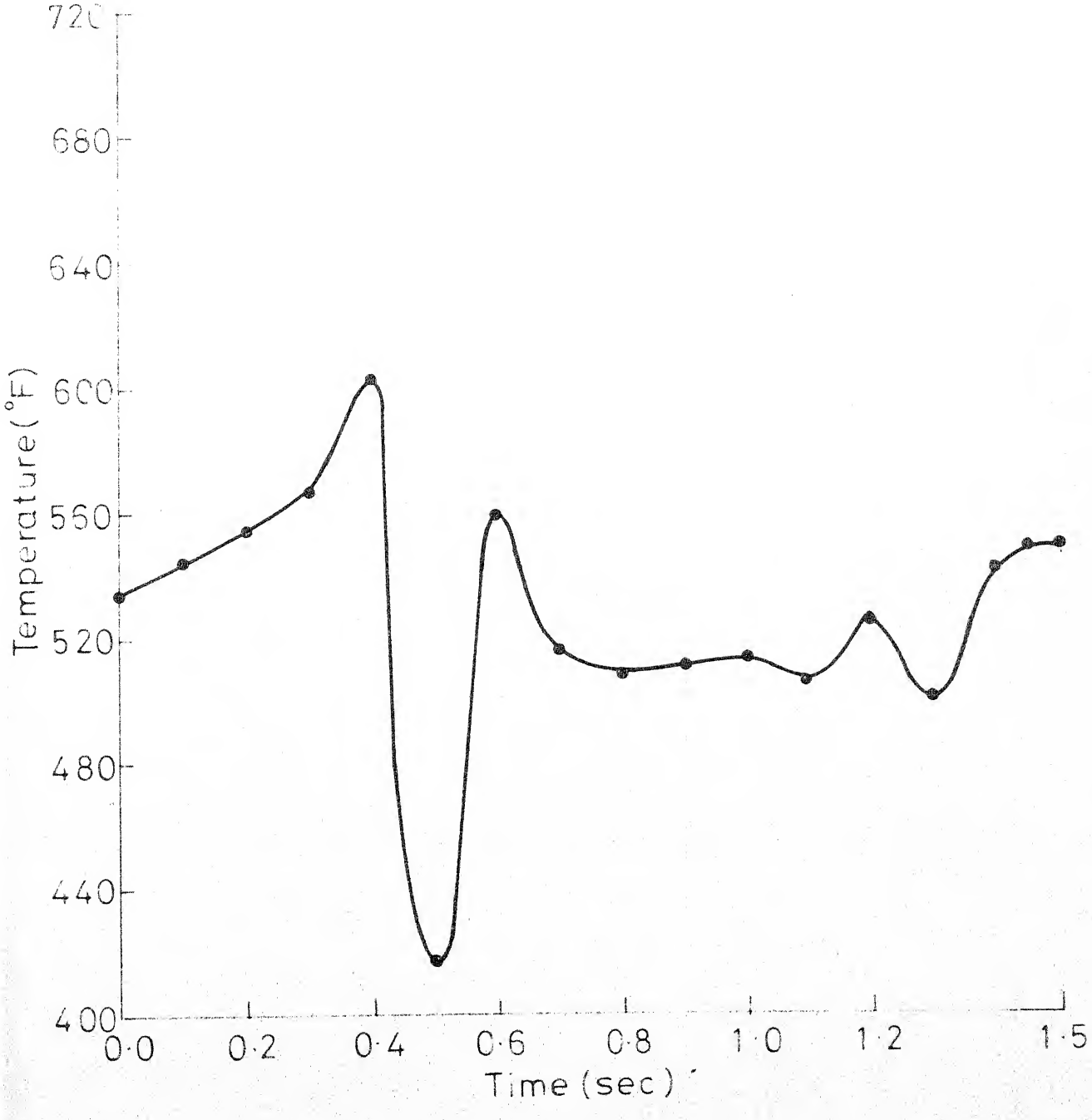


Fig. 5·4b Mass flow rate at the inlet of the secondary circuit was reduced by 5·0%

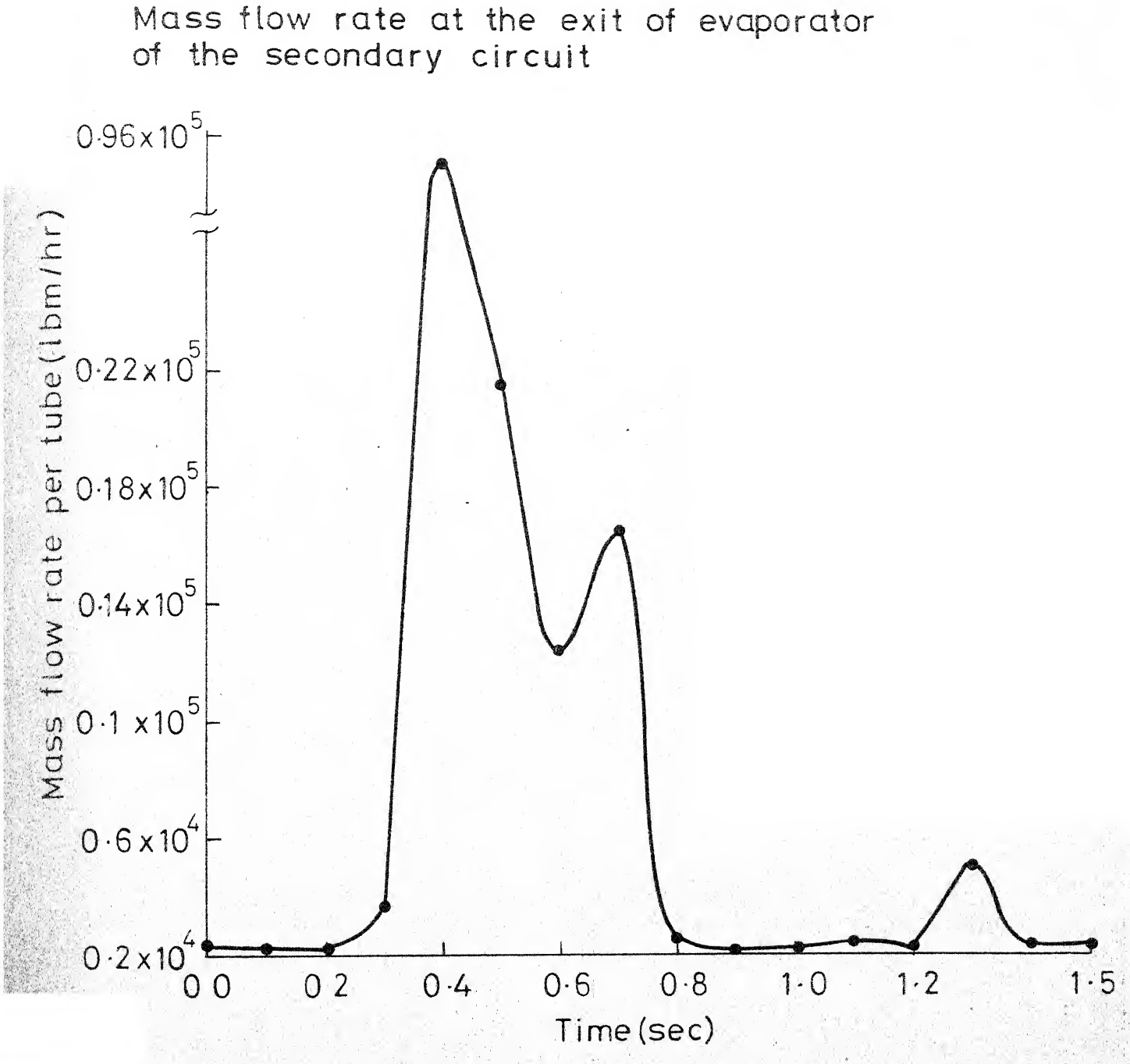


Fig. 5·4c Mass flow rate at the inlet of evaporator of the secondary circuit was reduced by 5·0%

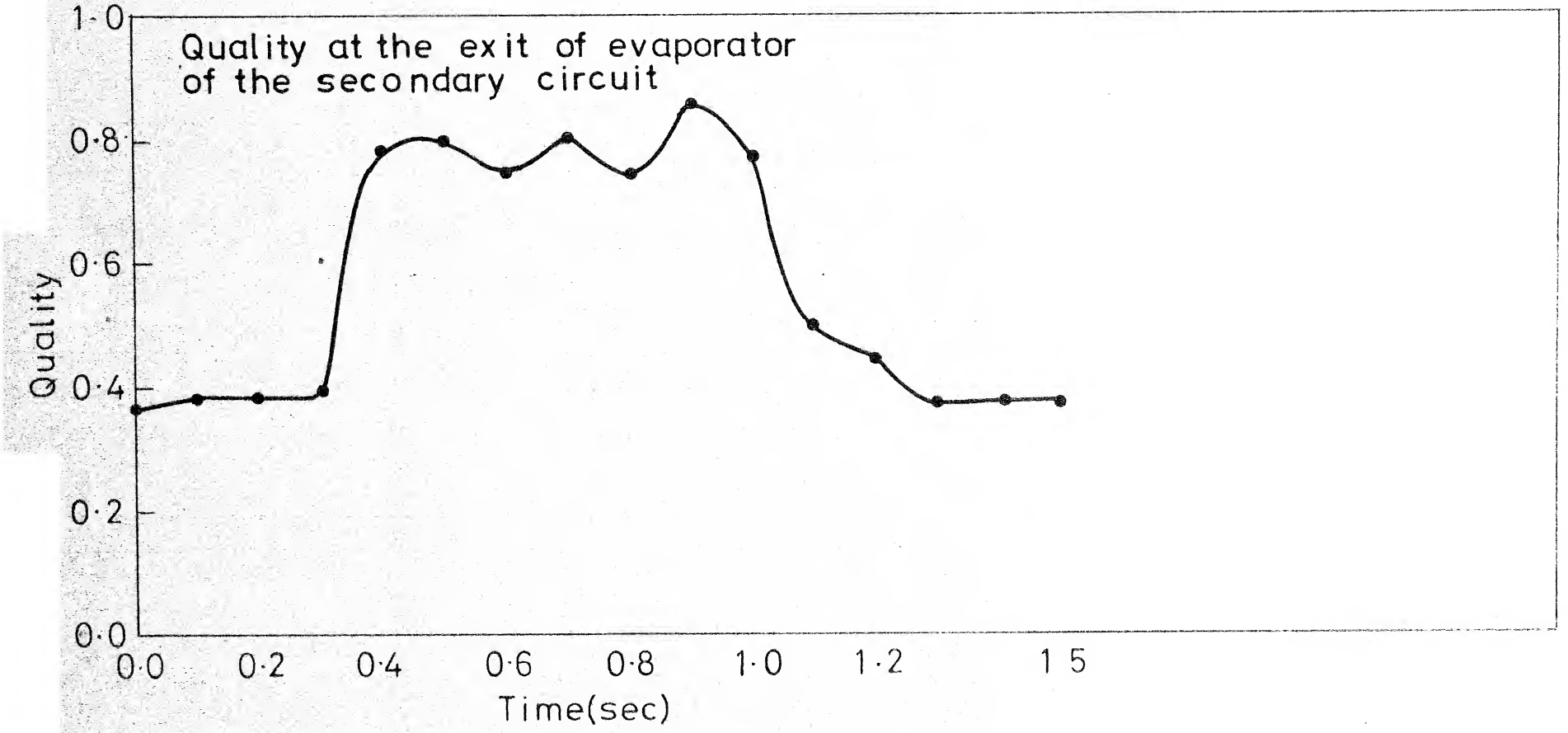


Fig. 5·4d Mass flow rate at the inlet of secondary circuit was reduced by 5·0%

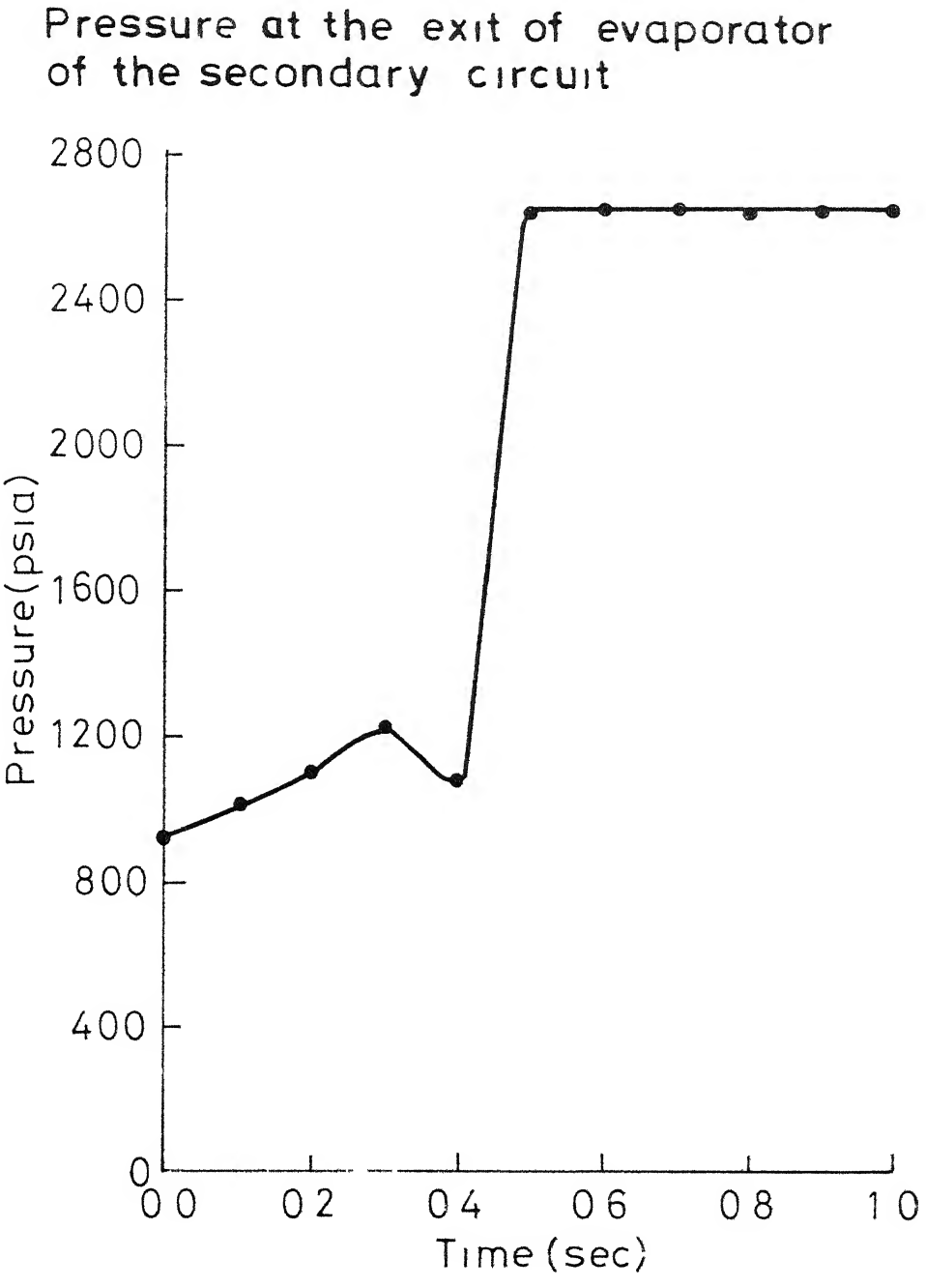


Fig.5·5a The pressure at the inlet of the secondary circuit was reduced by 30·0%

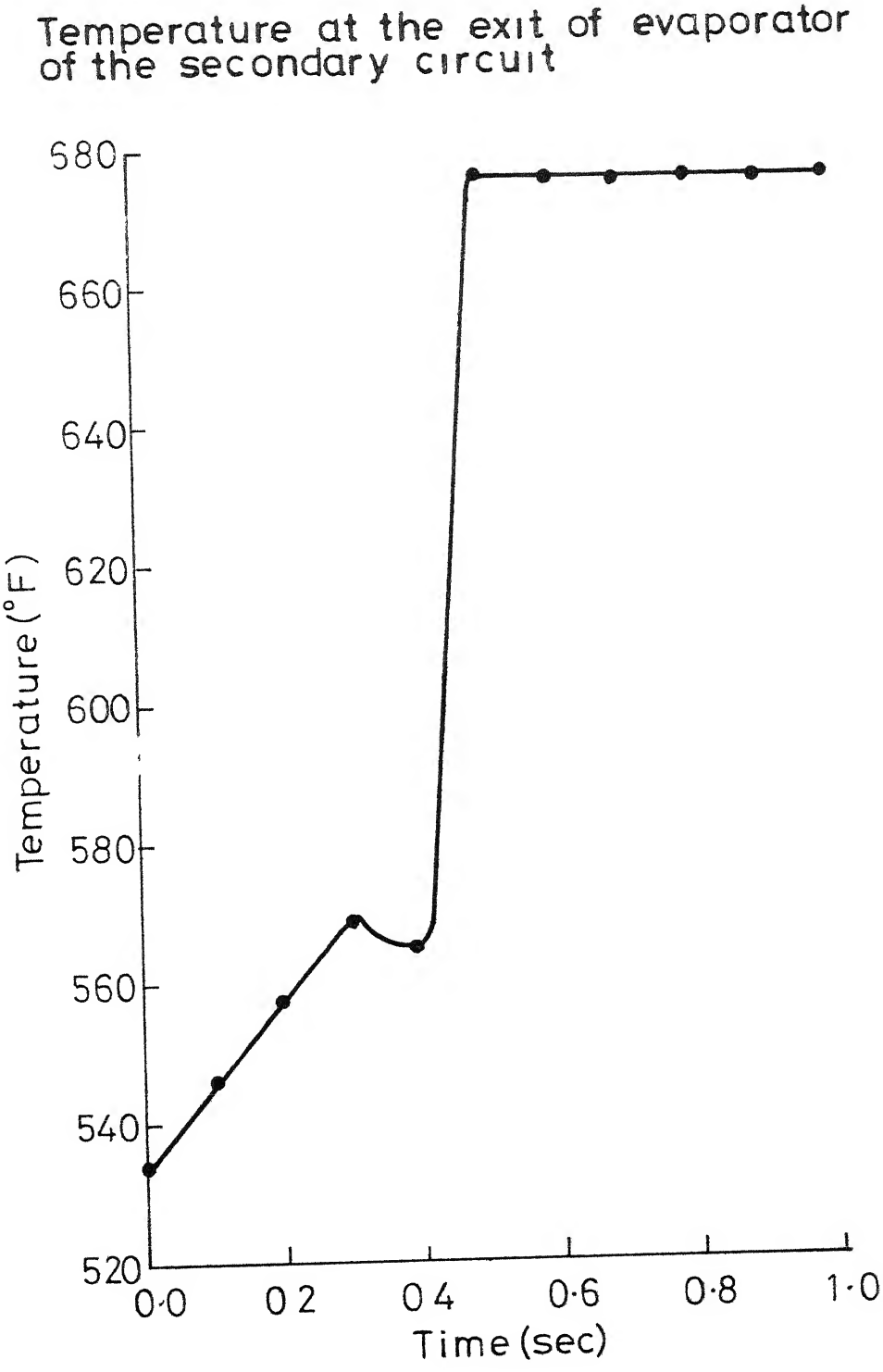


Fig. 5·5b The pressure at the inlet of the secondary circuit was reduced by 30·0%

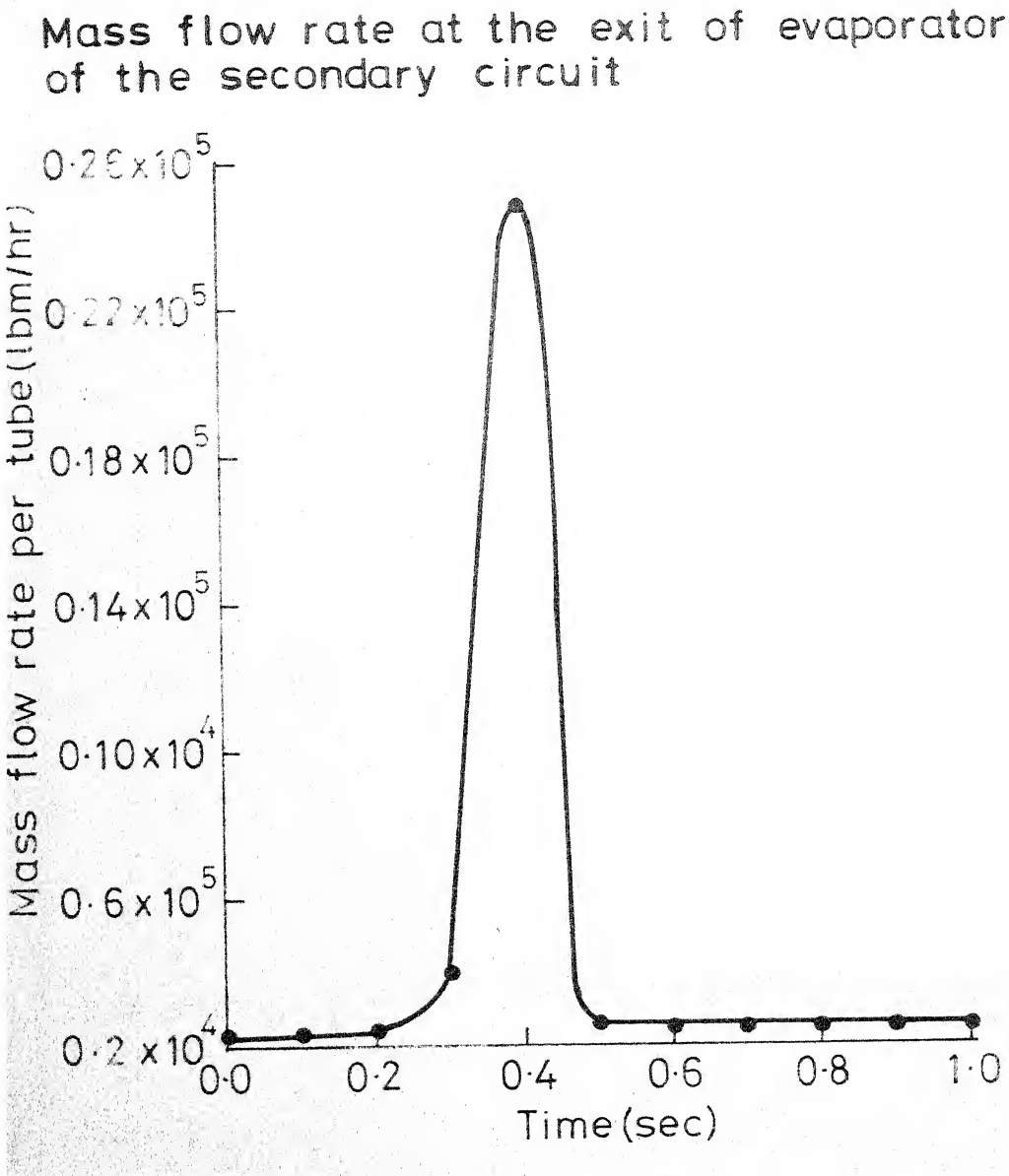


Fig. 5·5c The pressure at the inlet of the secondary circuit was reduced by 30·0%

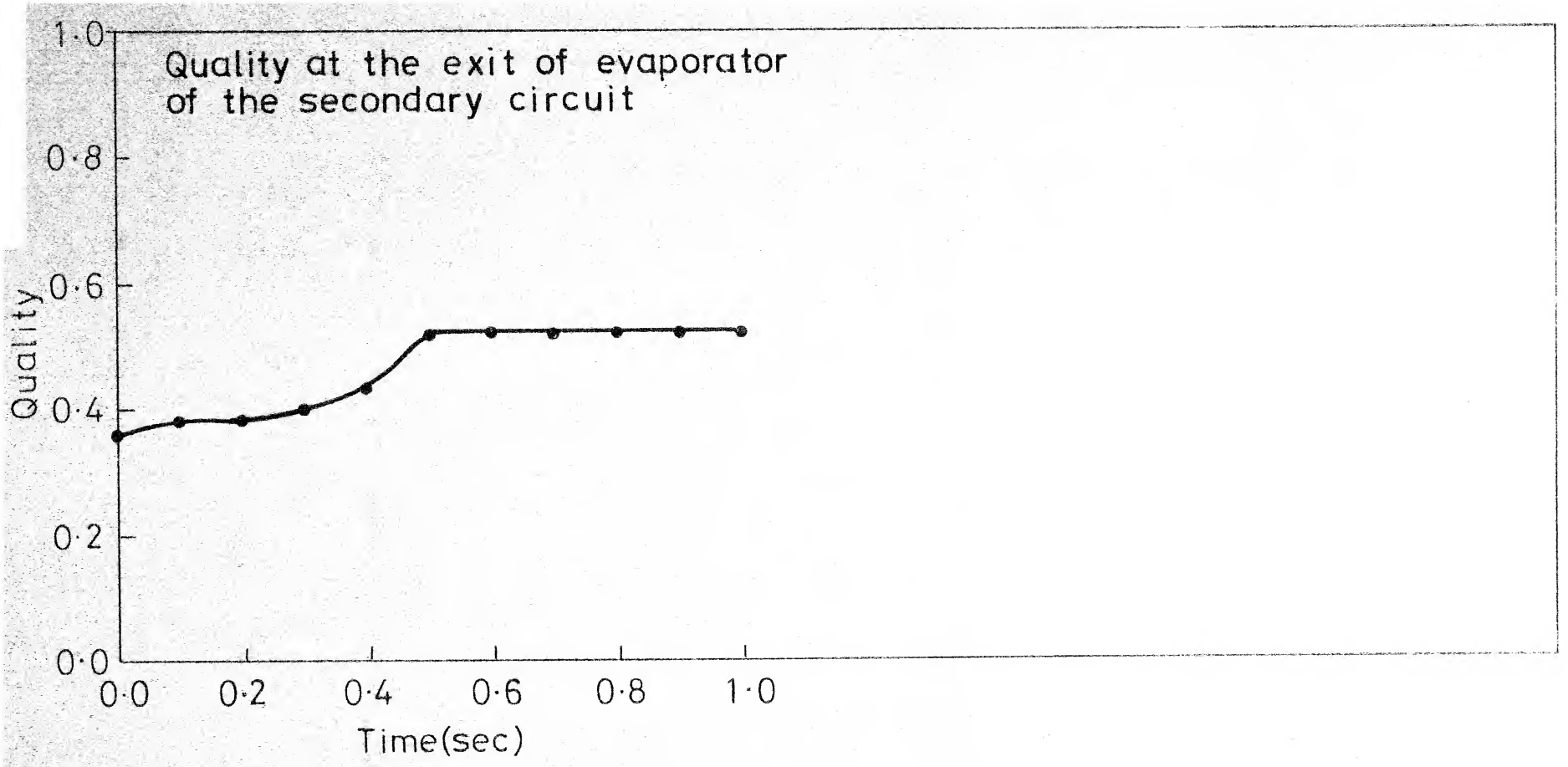


Fig. 5·5d The pressure at the inlet of the secondary circuit was reduced by 30·0%

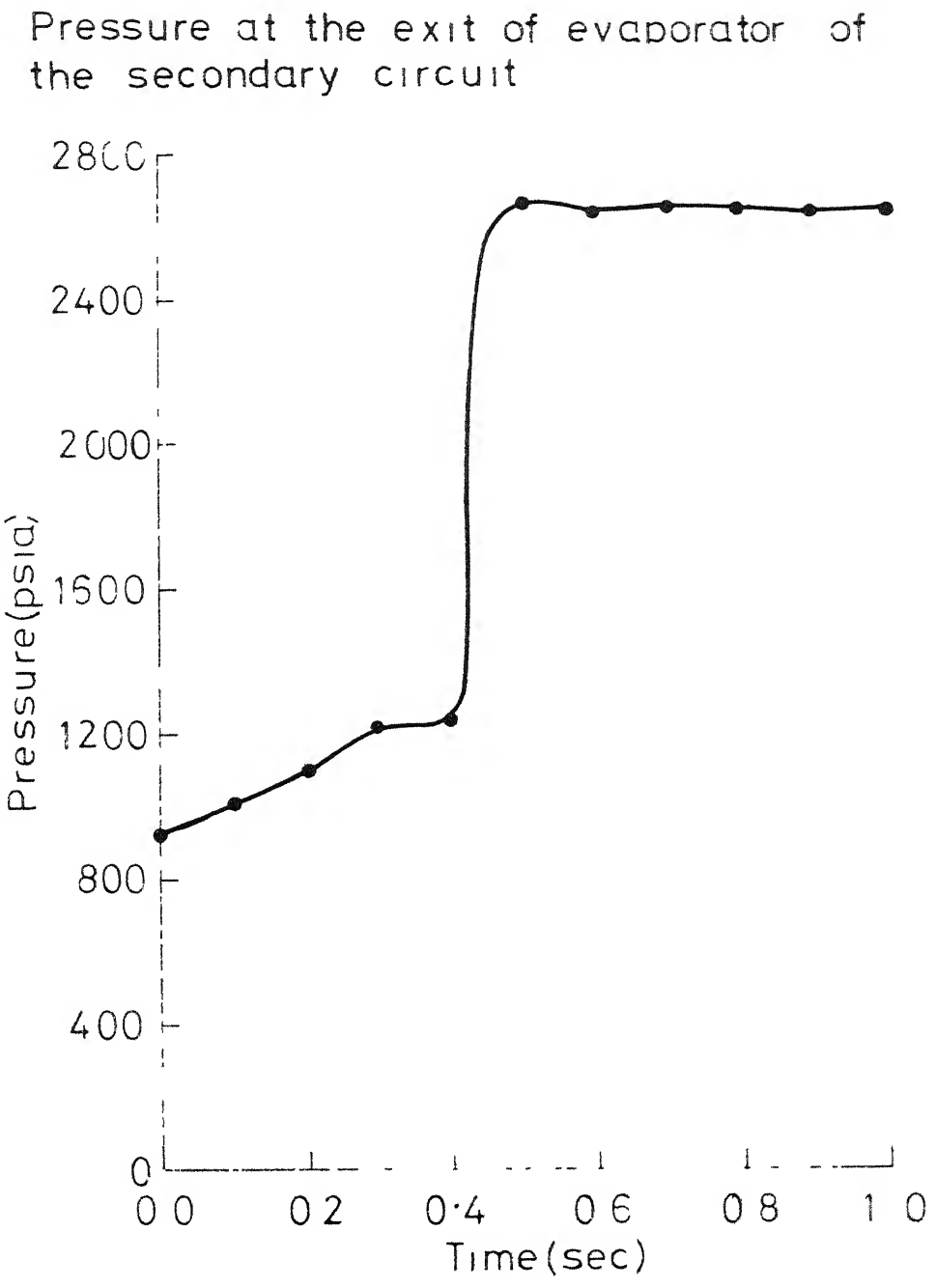


Fig. 5 6a The internal energy of secondary liquid was increased by 5%

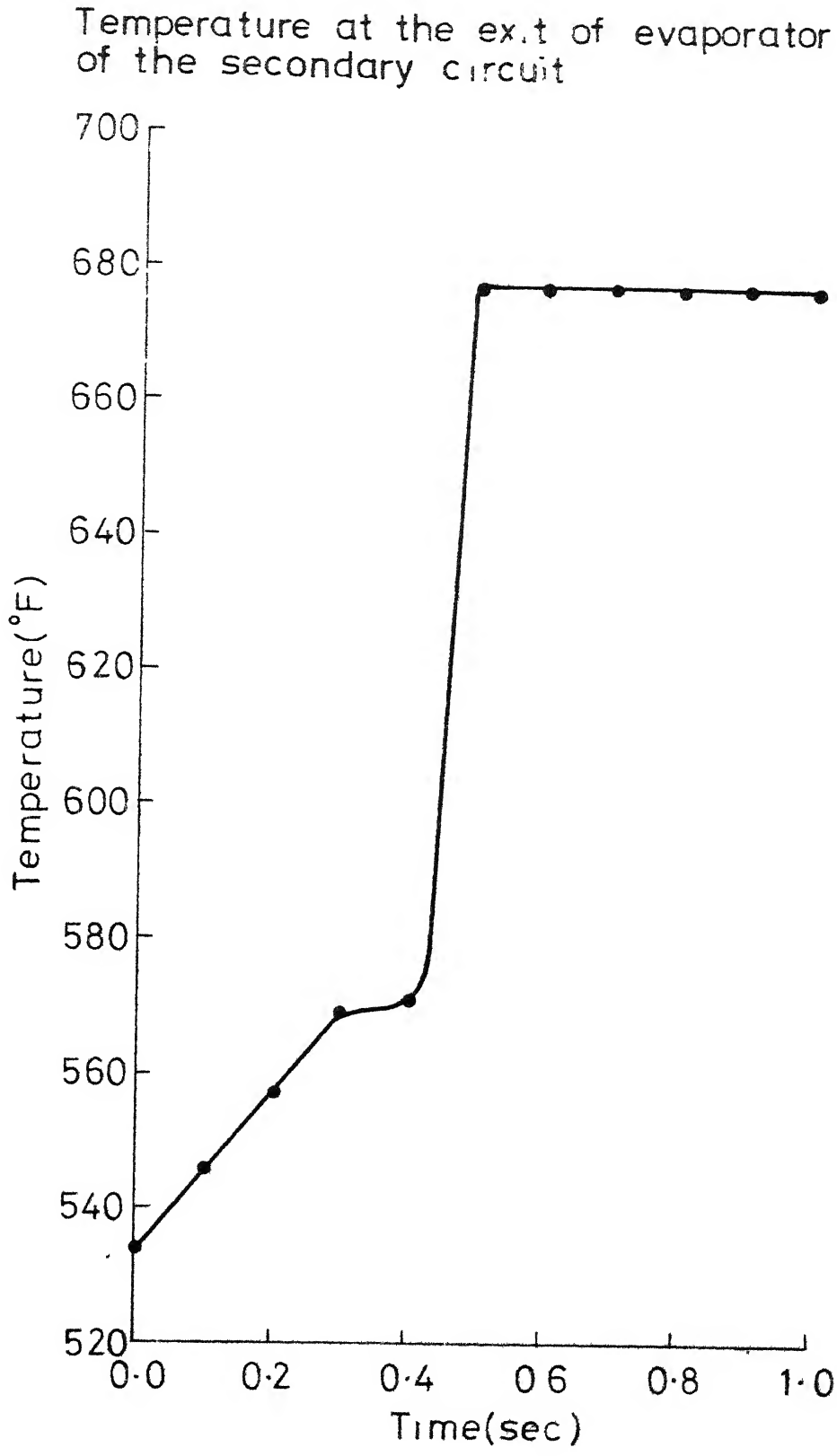


Fig. 5·6b The internal energy of secondary liquid was increased by 5·0 %

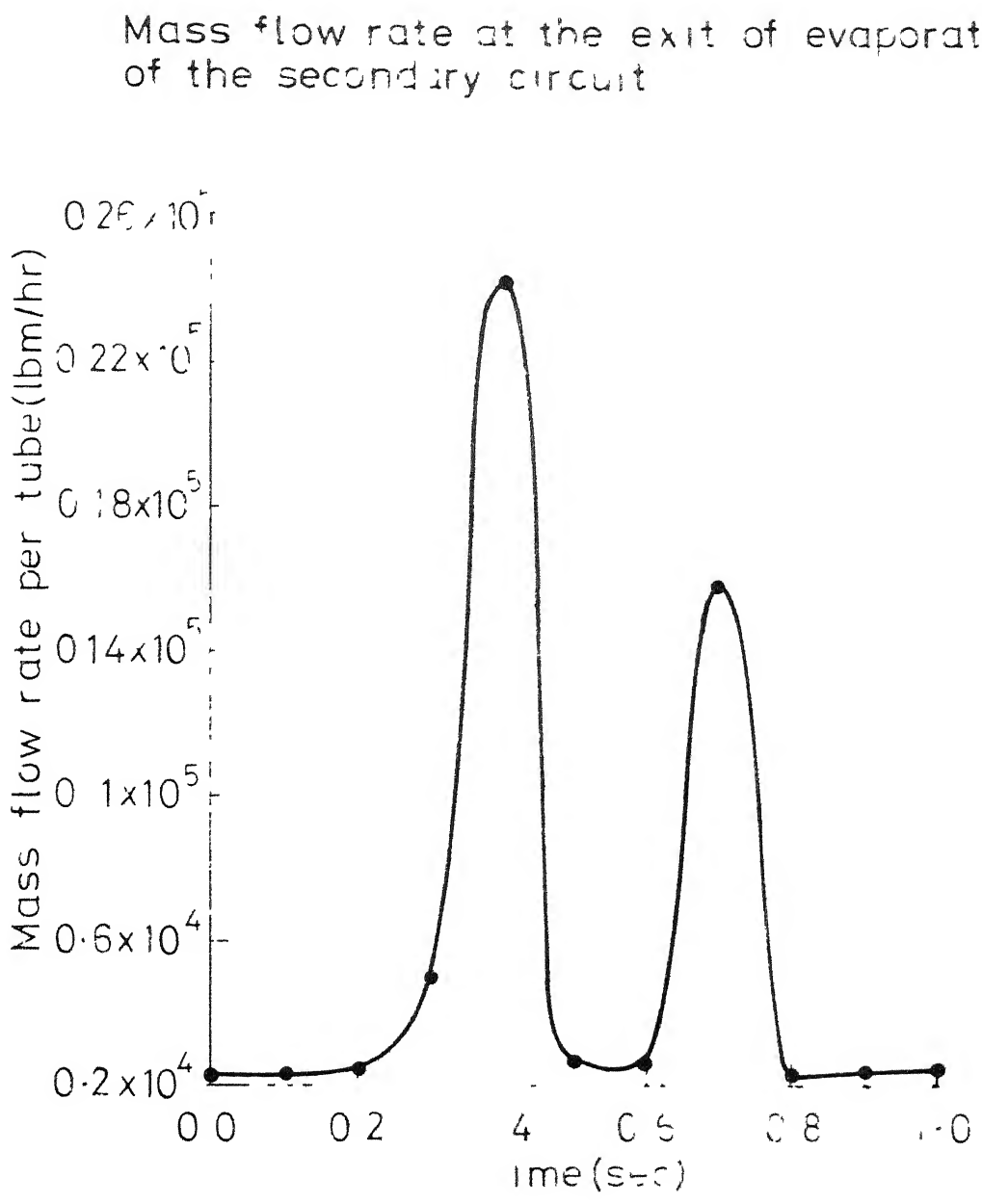


Fig. 5·6c The internal energy of secondary liquid was increased by 5·0%

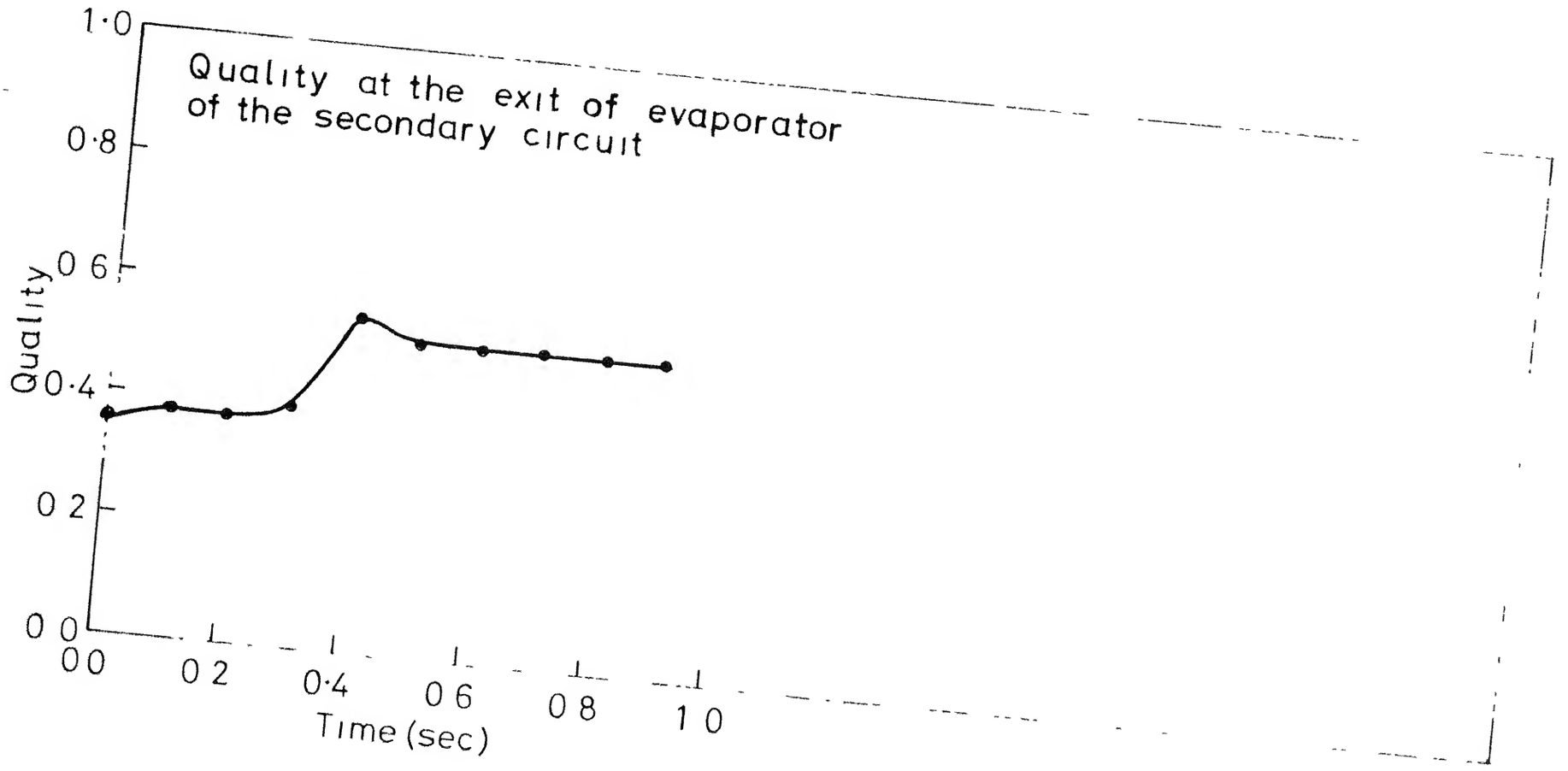


Fig. 5·6d The internal energy of secondary liquid was increased by 5·0%

APPENDIX A

We have

$$e = u + \frac{V^2}{2} + gZ$$

$$H = u + P/\rho$$

$$W = \rho AV$$

$$G = W/A$$

$$v = 1/\rho$$

The last two terms of equation 3.5 can be written as

$$\frac{d(We)}{dZ} + \frac{d}{dZ}(PAV)$$

$$= \frac{d(We)}{dZ} + \frac{d}{dZ}\left(\frac{WP}{\rho}\right)$$

$$= W\left\{\frac{de}{dZ} + \frac{d}{dZ}\left(\frac{P}{\rho}\right)\right\} \qquad (a)$$

Now $e = u + \frac{V^2}{2} + gZ = H - \frac{P}{\rho} + \frac{V^2}{2} + gZ$

$$\therefore \frac{de}{dZ} = \frac{dH}{dZ} - \frac{d}{dZ}\left(\frac{P}{\rho}\right) + V\frac{dV}{dZ} + g$$

i.e., $$\frac{de}{dZ} + \frac{d}{dZ}\left(\frac{P}{\rho}\right) = \frac{dH}{dZ} + g + V\frac{dV}{dZ} \qquad (b)$$

But $$V\frac{dV}{dZ} = \frac{W}{\rho A}\frac{d}{dZ}\left(\frac{W}{\rho A}\right) = \frac{1}{\rho}\left(\frac{W}{A}\right)^2\frac{d}{dZ}\left(\frac{1}{\rho}\right)$$

$$= v\,G^2\frac{dv}{dZ} \qquad (c)$$

From equation (a), (b) and (c) we get,

$$\frac{d(We)}{dZ} + \frac{d}{dZ}(PAV) = W\left(\frac{dH}{dZ} + g + v\,G^2\,\frac{dv}{dZ}\right)$$

So equation 3.5 will become

$$\ddot{q}\,\frac{dA_T}{dZ} - W\,\frac{dH}{dZ} - W\,G^2\,v\,\frac{dv}{dZ} - Wg = 0$$

APPENDIX B

Equation 3.6 is

$$-A\frac{dP}{dZ} - \frac{dF_K}{dZ} - \frac{d(WV)}{dZ} - A\rho g = 0$$

Now let us integrate this equation with respect to Z from the centre of control volume (n-1) to the centre of control volume n.

The first term will give

$$\int_{\substack{\text{centre of}\\ \text{C.V.(n-1)}}}^{\substack{\text{centre at}\\ \text{C.V.(n)}}} \frac{dP}{dZ}\, dZ = (P)_{\substack{\text{centre of}\\ \text{C.V.(n)}}} - (P)_{\substack{\text{centre of}\\ \text{C.V.(n-1)}}}$$

$$= \bar{P}_n - O\bar{P}_{n-1}$$

where $\bar{P}_n = (P)_{\substack{\text{at the centre of}\\ \text{C.V.(n)}}}$

The second term will become

$$\int_{\substack{\text{centre of}\\ \text{C.V.(n-1)}}}^{\substack{\text{centre of}\\ \text{C.V.(n)}}} \frac{dF_K}{dZ}\, dZ = \int_{\substack{\text{centre of}\\ \text{C.V.(n-1)}}}^{\text{J.n.}} dF_K + \int_{\text{J.n}}^{\substack{\text{centre of}\\ \text{C.V.(n)}}} dF_K$$

$$= \frac{1}{2} \left[\bar{F}_{K,n-1} + \bar{F}_{K,n} \right]$$

'J.n ' represents junction n.

From the third term we get

$$\int_{\substack{\text{centre of} \\ \text{C.V.(n-1)}}} \frac{d(WV)}{dZ} \, dZ = W \int_{\substack{\text{centre of} \\ \text{C.V.(n-1)}}} dV + W \int_{\substack{\text{J.n} \\ \text{centre of} \\ \text{C.V.(n)}}} dV$$

$$= W.(V_{\text{at J.n}} - V_{\substack{\text{at the centre} \\ \text{of C.V.(n-1)}}})$$

$$+ W.(V_{\substack{\text{at the centre} \\ \text{of C.V.(n)}}} - V_{\text{at J.n}})$$

The last term will become

$$\int_{\substack{\text{centre of} \\ \text{C.V.(n-1)}}} A \rho g \, dZ = A \rho g \Delta Z = \frac{A g \Delta Z}{v}$$

So if G is in lbm/ft^2-hr and the pressure terms $\bar{P}_n$ and $\bar{P}_{n-1}$ are in psi, the equation 3.6 can be written as

$$\bar{P}_n = \bar{P}_{n-1} + \frac{1}{2.A} (\bar{F}_{K,n-1} + \bar{F}_{K,n}) - \frac{G}{144.g_c} (V_n - \bar{V}_{n-1})$$

$$- \frac{G}{144.g_c} (\bar{V}_n - V_n) - \frac{g}{144.g_c} \cdot \frac{\Delta Z}{v_n}$$

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[illegible]

INPUT SPECIFICATIONS [illegible] STEAM GENERATOR
-NUMBER OF CONTROL VOLUMES 10

-PRINCIPAL [illegible] REQUIRED 0.50000E-12

-MAXIMUM NO. OF ITERATIONS 1[illegible]

-ACCELERATION DUE TO GRAVITY 0.32174E+02 FT/SEC**2

[illegible]

CHARACTERISTICS OF THE STEAM GENERATOR

NUMBER OF TUBES 4671

EXT. DIAMETER 0.75000E+00 INCH

INT. DIAMETER 0.66[illegible]E+00 INCH

TOTAL HEAT TRANSFER AREA 0.48300E+05 FT**2

FORM COEFF. 0.00000E+00

SPECT [illegible] 0.10675E+01 INCH
[illegible] PITCH

PRIMARY CIRCUIT

PRESSURE AT ENTRY 0.22500E+04 PSI

TEMP. AT ENTRY 0.62000E+03 DEGREE F

ENTHALPY AT ENTRY 0.64040E+03 BTU/LBM

FLOW RATE 0.35550E+08 LB /HR

ESTIMATED STEAM PRESSURE 0.22300E+04 PSI

SECONDARY CIRCUIT

PRESSURE 0.11210E+04 PSI

TEMPERATURE 0.43000E+03 DEGREE F

ENTHALPY 0.40780E+03 BTU/LBM

VAPOUR PRESSURE 0.92000E+03 PSI

QUALITY 0.40000E+00

VAPOUR FLOW RATE 0.40859E+07 LBM/HR

RATE OF HEAT TRANSFER 0.32115E+10 BTU/HR

00110						
00120						
00130						
00140						
00150						
00160						
00170						
00180						
00190						
00191						
00199	3206.2	705.34	0.0541	0.0541	910.3	910.3
00200	3199.1	705.	0.044	0.0597	870.2	947.8
00300	3094.1	700.	0.0369	0.0758	823.9	995.6
00400	2895.	690.	0.0328	0.0945	784.2	1039.1
00500	2800.4	685.	0.0316	0.1032	770.1	1054.6
00600	2708.4	680.	0.0305	0.1115	757.2	1067.2
00700	2619.2	675.	0.0297	0.1201	745.5	1078.3
00800	2532.4	670.	0.029	0.1281	734.6	1087.9
00900	2366.2	660.	0.0278	0.1445	714.4	1104.9
01000	2208.8	650.	0.0268	0.1616	696.0	1118.7
01100	2060.3	640.	0.026	0.1799	678.7	1130.7
01200	1919.6	630.	0.0253	0.1993	662.2	1141.0
01300	1852.4	625.	0.025	0.2095	654.3	1150.
01400	1787.0	620.	0.0247	0.2402	646.5	1150.2
01500	1661.6	610.	0.0241	0.2426	631.5	1158.1
01600	1543.2	600.	0.0236	0.2666	616.8	1165.2
01700	1431.5	590.	0.0232	0.2931	602.6	1171.4
01800	1326.1	580.	0.0228	0.3217	588.9	1177.0
01900	1226.7	570.	0.0224	0.3528	575.4	1181.9
02000	1133.4	560.	0.0221	0.3869	562.2	1186.3
02100	1045.6	550.	0.0218	0.4239	549.3	1190.2
02200	962.8	540.	0.0214	0.4647	536.6	1193.3
02300	885.2	530.	0.0212	0.5097	524.2	1196.1
02400	812.68	520.	0.0209	0.5591	511.9	1198.4
02500	744.55	510.	0.0207	0.6139	499.8	1200.4
02600	680.8	500.	0.0204	0.6748	487.8	1202.
02700	621.44	490.	0.0202	0.7421	476.01	1203.3
02800	593.28	485.	0.0201	0.7786	470.18	1203.8
02900	566.12	480.	0.0200	0.81742	464.37	1204.2
03000	539.9	475.	0.0199	0.8578	458.59	1204.5
03100	514.7	470.	0.0198	0.9006	452.84	1204.7
03200	490.43	465.	0.0197	0.9459	447.1	1204.9
03300	466.97	460.	0.0196	0.9941	441.42	1203.
03400	444.35	455.	0.0195	1.0451	435.74	1205.
03500	422.60	450.	0.01943	1.099	430.11	1206.
03600	401.7	445.	0.01934	1.156	424.49	1204.9
03700	381.59	440.	0.01926	1.2166	418.91	1204.8
03800	362.27	435.	0.01918	1.2809	413.35	1204.6
03900	343.71	430.	0.0191	1.3494	407.8	1204.3
04000	308.82	420.	0.01894	1.4995	396.78	1203.5
04100	276.72	410.	0.01871	1.7632	380.4	1201.8
04200	247.25	400.	0.01864	1.8632	374.97	1201.2
04300	220.29	390.	0.0185	2.207	358.8	1199.2
04400	195.7	380.	0.01836	2.336	353.45	1198.4
04500	173.33	370.	0.01823	2.625	342.79	1196.6
04600	153.01	360.	0.01811	2.958	332.19	1194.7
04700	134.62	350.	0.01799	3.342	321.64	1192.6
04800	117.99	340.	0.01788	3.789	311.14	1190.3
04900	103.03	330.	0.01776	4.31	300.69	1187.8
05000	89.65	320.	0.01765	4.915	290.29	1185.3
05100	77.68	310.	0.01755	5.630	279.92	1182.5
05200	67.01	300.	0.01745	6.471	269.6	1179.7
05300	57.55	290.	0.01735	7.465	259.31	1176.7
05400	49.2	280.	0.01726	8.651	249.06	1173.7
05500	41.85	270.	0.01717	10.07	238.84	1170.6
05600	35.43	260.	0.01708	11.771	228.65	1167.3
05700	29.82	250.	0.017	13.841	218.48	1163.8
	24.97	240.	0.01692	16.324	208.34	1160.4
	20.78	230.	0.01684	19.3888	198.22	1156.9
06000	18.915	225.	0.01681	21.17	193.18	1155.1
	17.188	220.	0.01677	23.16	188.14	1153.3
	14.696	212.	0.01672	26.83	180.07	1150.4
	14.123	210.	0.0167	27.83	178.06	1149.6
	13.031	206.	0.01667	30.01	174.03	1148.1
	12.01	202.	0.01665	32.39	170.01	1146.6
	11.525	200.	0.01663	33.67	167.99	1145.8
	10.605	196.	0.01661	36.4	163.97	1144.3
	9.744	192.	0.01658	39.40	159.95	1142.8
	9.336	190.	0.01657	41.01	157.95	1142.1
	8.566	186.	0.01654	44.45	153.93	1140.5
	7.849	182.	0.01652	48.24	149.92	1138.9

20
25
30
35

```
7.51          180.          0.01651     50.28       147.91      1138.1
6.869         176.          0.01648     54.66       143.9       1136.5
6.272         172.          0.01646     59.52       139.89      1134.9
5.99          170.          0.01645     62.14       137.89      1134.
5.46          166.          0.01643     67.78       133.90      1132.4
4.97          162.          0.0164      74.02       129.88      1130.7
4.739         160.          0.01639     77.39       127.87      1129.9
4.305         156.          0.01637     84.68       123.87      1128.3
3.904         152.          0.01635     920.81      119.87      1126.6
3.716         150.          0.01634     97.2        117.87      1125.7
3.363         145.          0.01632     106.74      113.88      1124.1
3.039         142.          0.0163      117.39      109.86      1122.4
2.887         140.          0.01629     123.18      107.888     1121.6
2.603         136.          0.01627     135.75      103.88      1119.9
2.343         132.          0.01626     149.85      99.89       1118.2
2.221         130.          0.01625     157.57      97.89       1117.4
1.995         126.          0.01623     174.28      93.9        1115.7
1.768         122.          0.01621     193.18      89.91       1114.
1.692         120.          0.0162      203.47      87.91       1113.2
1.512         116.          0.01619     226.2       83.92       1111.4
1.35          112.          0.01617     251.6       79.93       1109.6
1.274         110.          0.01617     265.7       77.94       1108.8
1.1338        106.          0.01615     296.5       73.95       1107.
1.0072        102.          0.01614     331.5       69.96       1105.2
0.9487        100.          0.01613     350.8       67.97       1104.4
0.8403        96.           0.01612     393.2       63.98       1102.7
0.7429        92.           0.01611     441.7       59.99       1100.9
0.698         90.           0.0161      468.4       58.         1100.1
0.6153        86.           0.01609     527.6       54.01       1098.4
0.5409        82.           0.01608     595.8       50.02       1096.6
0.5067        80.           0.01607     633.7       48.02       1095.8
0.444         76.           0.01607     718.        44.03       1094.1
0.3883        72.           0.01606     814.9       40.04       1092.3
0.3628        70.           0.01605     868.18      38.05       1091.5
0.3162        66.           0.01604     989.6       34.06       1089.8
0.2749        62.           0.01604     1129.7      30.06       1088.0
0.2561        60.           0.01603     1208.1      26.07       1087.2
0.2219        56.           0.01603     1383.5      24.07       1085.5
0.1918        52.           0.01603     1588.4      20.07       1083.7
0.178         50.           0.01602     1704.9      18.07       1082.9
0.142         44.           0.01602     2271.8      10.06       1079.4
0.1315        42.           0.01602     2271.8      10.06       1079.4
0.1217        40.           0.01602     2445.1      8.05        1078.6
0.1126        38.           0.01602     2632.2      6.04        1077.7
0.1041        36.           0.01602     2836.6      4.03        1076.9
0.0961        34.           0.01602     3060.4      2.01        1076.
0.0886        32.           0.01602     3305.7      0.01        1075.1
   .1      E03    .2      E03    .3      E03    .4      E03    .5      E03    .6      E
   .62     E03    .64     E03    .66     E03    .68     E03    .69     E03    .70     E
   .68     E02    .1679   E03    .2694   E03    .3747   E03    .4881   E03    .6281   E
   .6668   E03    .7117   E03    .7949   E03    .8961   E03    .1104   E04    .12746  E
  .26127 E-2    .22714 E-2    .18834 E-2    .10506 E-2   -.56072 E-3   -.84505 E
-0.136850E-1-0.200860E-1-0.469920E-1-0.729800E-1-0.167930E-00-0.227480E
     0.0E00        0.0E00        0.0E00 0.490750E-7 0.105280E-6 0.810680E
  .13558 E-5    .18628 E-5    .53821 E-5    .75397 E-5    .19146 E-4    .24645 E
.001          .003          .007          0.03          0.1           1.0
    0.781622E+00    0.174974E+01    0.203137E+01    0.247544E+01    0.23912
    0.259975E+01    0.180746E+01    0.215697E+01    0.884860E+00    0.73168
    0.314700E+00    0.324614E+00    0.734131E-01    0.409955E-01    0.00000
    0.832909E+00    0.177495E+01    0.201709E+01    0.253467E+01    0.26337
    0.246342E+01    0.172250E+01    0.698617E+00    0.783596E+00    0.89893
    0.386846E+00    0.965628E-01    0.189336E+00   -0.449483E-01    0.12451
   -0.298891E+00   -0.393882E+00   -0.134627E+00   -0.948287E+00    0.60137
   -0.889145E-01    0.676796E+00    0.304400E+00    0.939490E-01   -0.22198
    0.333253E+00    0.189369E+00   -0.280533E-01    0.386182E-01   -0.13888
   -0.987524E+00   -0.213213E+01   -0.216871E+01   -0.211601E+01   -0.20987
   -0.147847E+01   -0.144601E+01   -0.107155E+01   -0.574207E+00   -0.14319
    0.199020E+00    0.302126E+00   -0.675625E-02   -0.547085E-01   -0.70141
   -0.348688E+00   -0.244438E+00   -0.463406E+00   -0.383516E+00   -0.62853
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